ECONOMIC GEOLOGY

VOL. XXIII SEPTEMBER, 1928 No. 6

REPORT OF THE COMMITTEE ON PROCESSES OF ORE DEPOSITION.[1]

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ORGANIZATION.

ON April 24, 1926, at the annual meeting of the Division of Geology and Geography of the National Research Council, it was recommended that a committee be appointed to consider the processes of ore deposition. Such a committee was organized in the spring of 1927, composed of Doctors L. C. Graton, W. Lindgren, Chairman, D. F. Hewett, Adolph Knopf and F. L. Ransome, but in the short time available until the annual meeting little could be accomplished. In the fall of 1927 five new members, Doctors E. T. Allen, E. S. Bastin, W. H. Emmons, G. F. Loughlin and R. C. Wells, were added to the original five, making a total of ten members. The Committee has held several meetings during the year though in no one meeting was it possible to have the whole committee represented. Much consultation and discussion has, however, been effected by correspondence and the five members residing in Washington have frequently met.

PRESENT STATE OF RESEARCH.

The Chairman, considering the first duty of the Committee to be a review of the present state of research on the subject of ore deposition, took up a statistical study of this aspect and at the

[1] Presented at the meeting of the Division of Geology and Geography of the National Research Council, April 28, 1928.

meeting of the American Institute of Mining and Metallurgical Engineers in February, 1928, set forth the results of such an investigation.[2] The opinion was here expressed that although the Committee would not be able to solve the many complex problems involved it could clear the way, survey the field, state the problems and encourage systematic research. It was shown that the total annual number of papers dealing with geology, mineralogy and paleontology of North America is now about 1400. A large proportion of these papers have some bearing on economic geology; comparatively few deal with pure research; still fewer deal with research on ore deposition. For 1926 the papers on ore deposition number 179; those considering ore deposits in the United States number 106; ore deposits in Canada 56; ore deposits in Mexico, The Antilles and Central America 17. A few articles consider ore deposits in South America or elsewhere. It is evident that at the present time this indicates a more intense interest in the subject in Canada than in the United States, considering production and population. Many of the papers are purely descriptive and embody little of importance in research. One may say that out of 179 papers only about 25 per cent. contribute anything new and important in research and in most of these the research is a by-product of an investigation undertaken for purely economic purposes. For an industry which (in North America) yields nearly $2,000,000,000 worth of refined metals the showing, as far as research in ore deposits is considered, is surprisingly poor and seems to indicate a deplorable lack of appreciation of the value of scientific study.

In the paper mentioned a definition of research is attempted. It is shown that any description of an ore deposit normally contributes something new; a statistical paper likewise contributes something not previously known, but unless some entirely new facts are discovered, or some comparative statistical studies are undertaken, or some generalizations are deduced such papers are to be considered only as a low grade of research. It is rather

[2] "Research in Processes of Ore Deposition," Tech. publ. No. 78, issued with *Mining and Metallurgy*, Feb. 1928, pp. 14.

the exception when an article deals primarily with research. Economics is usually the leading motive and, as stated above, the research material is a by-product. The utilitarian spirit is rampant.

This applies particularly to the official surveys whose leaders are likely to feel that they should not expend public money for anything but investigation of immediate practical interest for the mining industry, and seem slightly apologetic when pure research is considered. The universities are less hampered in this respect but even these are often more or less connected with official surveys and the time which the authors can afford to spend on research problems is limited.

Research work of the highest order is that which is furnished by independent laboratories like the Geophysical Laboratory of Washington, but they have little opportunity to concern themselves with processes of ore deposition.

On the whole it may be said that research in processes of ore deposition is in an unsatisfactory state in spite of many creditable individual efforts. Successful research means able men available and more or less money to allow such men to devote their time to the work. Undoubtedly we have able men though the majority of these, by necessity or by choice, have concentrated more on the economical than on the scientific side of the work.

FUNDS AVAILABLE FOR RESEARCH.

The funds available for research are very small in comparison to those at the disposal of the physical, chemical, agricultural and medical sciences. We may classify these funds as follows:

1. *Governmental Sources, Mainly Including Allotments for Public Surveys.*—As already explained comparatively little of such moneys are used for research of high standard. There appears to exist no reason why research could not be undertaken, as indeed it is done, and on a large scale, in the Department of Agriculture, but of course, given small appropriations, the necessity always exists of turning most of the money into problems

of immediate economic importance. The appropriations for economic geology, scant beyond reason, should certainly be increased.

2. *Educational Sources. Mainly Funds at the Disposal of Universities and Colleges.*—These funds are usually scant though most institutions have a little of such money available and there is a growing appreciation of the necessity of research. Frequently, the instructors are so overloaded with teaching that research is confined to such time as can be snatched from their educational work. There are very few fellowships available which can be awarded to promising students. Good work is being done but it is accomplished in the face of many difficulties. Little cooperation exists and the work is sporadic rather than systematic.

3. *Private Sources.*—Among these are counted research establishments like those of the Carnegie and Rockfeller Institutions which have done so much to encourage research. Further moneys are those contributed by the metal mining industry and the very small amount contributed by private individuals. The first two groups of institutions under their present organization are doing little to further research in ore deposition and have no fellowships for such purpose, in fact, have no geological fellowships at all. The Geophysical Laboratory has accomplished some very important work bearing upon the problems of ore deposition but is more concerned with strictly geochemical and mineralogical questions.

Much should be expected from the companies and individuals connected with the metal mining industry for they should receive the benefits of research work in ore deposition. In spite of a few notable exceptions this industry appears to take little interest in work of this kind and has contributed little money for this purpose except for the investigation of some of their own most pressing, mainly structural problems. This is an unfortunate state of affairs and suggests a regrettable lack of vision.

Some of the problems suggested in the following pages may be properly taken up by various surveys and universities, but a large proportion of them demands the facilities of a properly equipped

laboratory of the type of the Geophysical Laboratory of Washington. It was proposed in the paper here summarized that the mining industry should take steps to organize such a research laboratory under the control of the U. S. Geological Survey or the Research Council. Its activities might conveniently be enlarged so as to include processes of mineralization in general which may be of importance to the study of ores and non-metallic products.

PROBLEMS OF ORE DEPOSITION.

It is certainly not the purpose of the present report to belittle the work done in this country or on ore deposition. It is in fact a most creditable record involving the description of the camps and districts of a large part of the continent. It includes the recording of an enormous array of new facts carried on with little money and by a small force of workers. This mass of material calls for systematic study and a search for generalizations, and it is in this line that sufficient efforts have been lacking. Each author usually leaves off where his special work has been completed and as a rule is not able to devote the time necessary for conclusions and generalizations.

The investigations needed fall into five divisions, the last of these involving problems which can only be solved by laboratories having equipment for complex chemical and physical research:

1. General problems related to assumptions and definitions.
2. Distribution of ore deposits and relation to accompanying rocks.
3. Structural features of ore deposits.
4. Mineralogical and chemical features.
5. Physico-chemical investigations of the processes of ore deposition.

GENERAL PROBLEMS AS TO ASSUMPTIONS AND DEFINITIONS.

In a manuscript entitled "Preliminary Outline of Proposed Inventory of the Problems of Ore Geology," Dr. Augustus Locke suggests that ore geology has picked its way not only from fact

to fact but also from one selected assumption to another and that these assumptions, though an essential basis for some of the broad conclusions, often lie hidden and forgotten. It becomes necessary to scrutinize these assumptions and the definitions of processes and structure. An excellent example of what is meant by this are the terms "pneumatolytic" and "pneumatolysis." It is evident that different meanings are attached to this expression by different people. Other terms needing careful scrutiny are replacement, diffusion, colloidal effects, critical temperature, pneumotectic deposits, magmatic extracts, deuteric minerals and "volatile matter." Much confusion undoubtedly results from this vagueness or difference in definitions and a valuable contribution to the geology of ore deposits would be to prepare a list of such terms indicating the present range in their usage. In stating important conclusions it is certainly incumbent upon the author to clearly define the meaning of the terms which he uses, and not leave the instruments of measurement in confusion.

DISTRIBUTION AND RELATION TO ACCOMPANYING ROCKS.

Valuable generalizations may be obtained by the study of the deposits within a given larger area, either arbitrarily defined, like a State, or contained in a certain geologic or physiographic unit, like the Appalachian Range.

A beginning in such work was made in Prof. Paper 68, U. S. Geological Survey, by Lindgren, Graton and Gordon in which this plan was carried out for New Mexico. It was followed up in Prof. Paper 111, by Butler, Loughlin and Heikes, in which the Utah deposits were taken up in a similar way. Among the noteworthy results obtained were the distribution of the copper deposits in the Red Beds, and the dependence of other classes of precious metals on Tertiary intrusives. A considerable number of deposits were found to have been formed in pre-Cambrian time. Excellent results would probably be reached by a similar study of Colorado, Arizona, Nevada and Idaho. Necessarily such work would require acquaintance with the geology of the particular state described. Such monographs tend to be bulky

but care should be taken not to include too many details. A wealth of observations lies buried in the literature and work like this serves to bring to light much old but valuable material.

Naturally it is difficult to exclude from consideration other important data relating to structure and mineralogy.

Another plan by which results may be attained more rapidly would be to take up the distribution of certain kinds of deposits over larger areas. For instance, we have no comprehensive account of the copper deposits in early Mesozoic sandstones and shales, in regard to which the views of origin are far apart. This would include the mapping of all known occurrences in Texas, Oklahoma, New Mexico, Arizona, Utah, Colorado and Idaho; surely such a review would help to establish the origin of these ores. A similar project would relate to the vanadium and uranium sandstones of the same age in a more restricted area including Utah, Colorado and New Mexico.

The lead-zinc deposits in the Paleozoic of the Mississippi valley and adjacent areas have never been comprehensively discussed. They reach from Ontario to Arkansas and from Tennessee to Wisconsin. Surely, their distribution stands in some connection with their origin and would constitute a fascinating problem. Why are they absent from the Cordilleran region? Naturally, it might be difficult to separate distribution from structure and mineralogy, but the investigation of distribution would at any rate be a preliminary problem.

There are so many problems of this kind that their enumeration would become tedious. I would merely suggest that a discussion of the distribution of epithermal veins in this country is wholly lacking but would be extremely interesting. A longer and more difficult investigation is that of the primary gold deposits of the Pacific Coast and their relation to the various intrusive rocks Here there is a possibility that the direction of these belts or zones may indicate important genetic facts. It is not necessary to cover the whole field in any of these problems at once. Review by States and more circumscribed regions will be useful.

The pre-Cambrian deposits of the Cordilleran region have

never been the subjects of a comprehensive study. Deposits of liquid magmatic origin are admittedly scarce on this continent. Would not a summary of their distribution and character prove interesting?

A much broader problem is suggested in the treatment of the deposits of North America from the standpoint of distribution and geological relations. By this is not meant a monographic treatment of all deposits but a critical review of their occurrence and origin. Obvious as this problem is, it has never been efficiently attacked. In connection with this there is need for good maps on which the distribution of mineral deposits is indicated.

Many more reviews of certain classes of ore deposits are desirable. Among them the following may be mentioned:

a. Concentrations of copper, vanadium, uranium, manganese, chromium and cobalt in sediments, along lines developed by Samojloff.[3] They may or may not have direct relation to bacterial processes.

b. Features conditioning the deposition of sedimentary iron ores as hematite, glauconite, chamosite or limonite. This would include a study of the literature and also experiments to show effect of both chloride and sulphate salinity on degree of hydration of iron. The effect may be produced by organic reactions or by direct precipitation.

c. A critical review of the literature relating to the pegmatites of basic rocks with special reference to their affinities with certain classes of ore deposits.

d. A critical review of the literature to correlate the mineralogy of pyrometasomatic (contact metamorphic) deposits with the types of igneous rocks with which they are associated. The sequence of progressive replacements near igneous contacts should be investigated.

e. A critical study of the relation of certain iron silicates like ilvaite, hedenbergite and fayalite to lead replacement deposits (mainly in northern Mexico) and the differences, if any, of these from pyrometasomatic deposits of the normal kind.

[3] *Miner. Mag.*, 1917.

General problems of immediate economic importance but which perhaps rather belong to the domain of the federal survey are (1) The resources of our metallic ores, (2) the rate at which these different classes are being exhausted, (3) probable trends of future production and (4) statistical research showing the production and relative importance of the several geologic divisions of ore deposits.

STRUCTURAL FEATURES OF ORE DEPOSITS.

The investigation of structural features involves many complex problems. Preliminary to their study comes the general theory of the origin of fractures and faults, which is not too familiar to geologists. This subject needs a review written for geologists with definite reference to concrete examples. Interesting experiments on the origin of fractures were carried out by Leith and Mead at Butte.[4] This line of investigation should be carried further and critically examined. A better and more scientific nomenclature than the present one could no doubt be proposed.

Studies of fractures over large areas are certain to yield important results. Few maps made show the trends of veins in such larger areas. The relations of fractures to folds and to the roofs of batholiths are important. In other words, is there any connection between ore deposits and the larger structural features of a region? Many such data are already available which only need to be collected and plotted.

The origin of ore-bearing "pipes" or chimneys is another subject of great interest. They may indeed have been produced in various ways. A recent view expressed by Mr. Locke that they may have been caused by collapse following "mineralization-stoping" deserves earnest consideration.

The structures of the so-called lenticular veins should be investigated; it is clear that there are several kinds but most of them are of the so-called high temperature type; how these openings were formed would constitute an interesting study. There are

[4] Testimony in the Black Rock-Superior Case, Butte, 1927.

many available reports on this subject from the Southern Appalachians, the Black Hills, Wyoming, Canada, and elsewhere which need to be studied and correlated. Naturally, this connects with the question just how these openings obtained their filling—say of gold-bearing quartz; also whether replacement is of importance in such veins.

Closely allied investigations should attempt to determine size, form and value of ore shoots in fissure veins. In many cases data are available to determine the value of ore shoots by equal value contours, to test Hoover's theory of ore shoots as concentric lenses with the highest values in the center. Is there any difference between ore shoots in veins with normal or reversed faulting? Other problems are related to the mode of filling, criteria of replacement, the mechanism of inclusions of country rock, the origin of transversely fibrous veins. On all of these subjects there is a large, often very polemic literature. A review of districts is desired in which the deposits follow large dislocations in preference to subordinate fractures, and vice versa. Many ore deposits have acquired a post-mineral sheeted structure; cases where there is new mineralization or concentration from the older ore on the sheeted surfaces should be investigated. Probably the study of the fracture systems in ores would be of interest. As a rule, too little detail is found in mine reports on this subject.

MINERALOGICAL AND CHEMICAL FEATURES OF ORES.

There is an overwhelmingly large literature relating to the composition of metallic ores. As summarized in the text-books the information is generally unsatisfactory. In each of the great classes of ore deposits there is a great deal to be done, both in critical review of old observations, and also in adding new material. Needless to say, the mineralogical composition is not only of immediate practical importance, but it contains also the key to the genesis. In view of recent progress in the study of ores by metallographic methods many of the old data have become questionable or erroneous.

There is to be considered (1) mineral composition, (2) chemi-

cal composition, (3) texture, and (4) paragenesis, or succession of the various minerals. The gangue minerals are equally important as the ore minerals, and their habit and crystallization will be found to give interesting points on the genesis of the deposits. Why, for instance, suggests W. T. Schaller, does calcite in certain deposits crystallize in tabular form parallel to the base while in other deposits the form is rhombohedral or scalenohedral?

There is wanted a critical list of minerals present in the California gold-quartz veins; in the high temperature veins and in the epithermal gold-silver veins. Similar descriptions of texture of ore and gangue are lacking except for individual mines and districts. There are many fine collections, public and private, of specimens of native gold which should be examined from a modern viewpoint Most of our information indicates that gold is usually one of the last minerals introduced. Is this a valid generalization for all gold?

Finally, the succession of the various minerals should be determined after the criteria for such paragenesis have been worked out. At present these criteria are in a more or less confused state and individual workers apply different rules. There has been no coöperation between the various investigators in this field. To deal with this matter a subcommittee of the Committee on Processes of Ore Deposition has been organized.

On the basis of such approved criteria the succession of minerals should be worked out. Most of the work so far has been concerned with deposits of magmatic affiliations, but interesting problems appear as to the succession of minerals in the Mississippi Valley lead and zinc region and in the copper ores of the "Red Beds."

It is curious that in practically all ores with magmatic relations the paragenesis begins with the hard minerals—pyrite, arsenides, cassiterite, iron oxides—and closes with the deposition of the soft lead and silver minerals. Sphalerite almost invariably follows pyrite and precedes chalcopyrite. The complex sulphur salts are usually among the last minerals to form. Only exceptionally is the order reversed.

Finally, the physico-chemical laws that govern this succession should be established. Attempts in this direction have been made by A. C. Spencer and others but as yet we are far from a solution of this problem.

Work of this kind requires coöperation; it does not involve elaborate experimentation to establish the facts but it is difficult for the official surveys to devote sufficient time and money to these problems. Here is where the lack of fellowships in research is severely felt; if progress is desired, money must be provided. Studies like those of Tolman and Rogers on magmatic ores and those of E. S. Bastin on problems of supergene ores should be encouraged.

Although much attention has been given to the problem of "zoning" of ore deposits, that is, the arrangement of minerals in vertical or horizontal zones (probably dependent upon decreasing temperature), there is still much to learn. Certain ore deposits show no "zoning." W. H. Emmons suggests that "zoning" is confined to deposits whose origin is in the roofs of batholiths. As stated here this problem merely relates to actual facts as shown in ore deposits, but in a wider sense it is intimately connected with the problem of the solubility of sulphides. Here chemists and geologists must coöperate.

PHYSICO-CHEMICAL INVESTIGATIONS.

We have now arrived at the discussion of the many physico-chemical problems which must be taken up as a basis for future research. Most of these can only be handled properly in a laboratory equipped for such research.

Movement of Solutions through Rocks.

One of the first problems demanding solution relates to the movement of solutions through rocks, mainly on capillary openings. This is therefore a problem of diffusion, but under varying conditions. The capillary openings may be those of a porous rock like sandstone or marble; instead of rocks, tubes packed with quartz sand, kaolin, etc., may be used. Very little is known about

these various phenomena. The following phases of the problem should be distinguished.

Rocks Not Attacked by the Solution.

a. Simple Solutions, Speed of Diffusion.
(1) in dry rocks (capillarity and diffusion).
(2) in rocks saturated with water (diffusion alone).

b. Complex Solutions.—Is there any separation taking place between the electrolytic, colloidal and gaseous components of the solution? How rapidly does this take place? To what extent are the various constituents held in adsorption by the rock minerals?

c. Simple and Complex Solutions.—How do they behave under various pressures and temperatures? How do they act when forced to move against a rising temperature gradient?

In these experiments we have to consider the work of Liesegang and Watanabé concerning diffusion in gels, and, also, recent experiments by Whitman in which silver salts were to diffuse through marble saturated with water. An important question is in how far dilute colloidal solutions—say of silica—are able to penetrate into rocks on capillary openings. Theoretically their power should be minimal, yet there may be considerable penetration.

Rocks Chemically Attacked by the Solution.—Here the problems become much more complicated and it is desirable to begin with simple conditions. They are really studies in replacement and its relation to diffusion aided by pressure, and open a wide vista of experimental research. Tubes filled with tightly packed material may be substituted for rocks although in such loose material replacement will not operate quite as it does in solid rocks.

Experiments can be made to reproduce oxidized minerals and supergene sulphides. W. H. Emmons writes that such experiments (not published) have been carried on in his laboratory by

passing solutions very slowly through long tubes in contact with various ores and gangues. Secondary ores were produced but the work is long and tedious. Similar experiments have been made at higher temperatures but all this work is difficult and expensive and calls for special laboratory facilities.

Problems of serpentinization, sericitization and alunitization [5] may be attacked in a similar way.

Further experimental work of this kind relates to the replacement of limestone by silica at moderate temperatures; work along this line has actually been done some sixty years ago. It relates further to the replacement of limestone by metallic sulphides in colloidal or electrolytic solution. It relates further to the action of water containing H_2S on rocks with iron silicates such as andesite or basalt. Naturally these experiments would lead to attempts to replace one sulphide by another.

One of the main difficulties is to obtain recognizable end products but here the X-ray analysis steps in and often extends invaluable aid.

Problems in Colloidal Chemistry.

It is universally admitted that colloidal processes play an important part in the zone of oxidation. It is not so generally known that the colloidal behavior is not confined to low temperatures; at least, geologists have hardly become conversant with these facts. It may be pointed out that red Fe_2O_3 sol is stable at temperatures of 200° C.; that silica is certainly carried in colloidal solution at 300° C.; that metals are colloidally dispersed in melts of metallic chlorides, say of silver and lead at about 600° C.; that dispersions of colloidal kinds may be observed in metals and in "ruby glass."

The great importance of colloidal dispersion is that difficulty soluble substances may be easily transported in colloidal form; for instance, gold, platinum, iron oxide, silver chloride. A wonderful field for investigation is here opened. An abundance of facts lies deeply buried in the chemical literature.

[5] R. J. Leonard, Econ. Geol., 22, pp. 14–17, 1927.

Precipitation of Colloidal Oxides.—The oxides of iron and manganese with characteristic colloform texture are often found in the zone of oxidation. It is desirable to extend further the examinations of Udluft's and Behren's (published in the *Zeitschrift. f. prakt. Geol.*) and to ascertain under what conditions such sols of the hydroxides of iron and manganese are mutually precipitated. The activity of such sols in absorbing arsenic, phosphorus, vanadium, barium and potassium is another subject of interest. The stability of such sols in the presence of electrolytes and colloidal silica should be tested. Their mode of origin should be ascertained: they may result from hydrolysis of certain salts; mutual precipitation often occurs when various oxide sols are mixed. The coagulated products should be slowly dried and allowed to crystallize at higher temperatures to determine what metacolloid minerals are ultimately formed.

Another problem relates to the corresponding behavior of cobalt and nickel oxides. As to nickel it is of importance, for instance, in the iron deposits of Cuba. The nickel in these is derived from serpentine and the ores may eventually prove of importance as a source of nickel. Here again the part played by silica should be investigated.

Still another problem relates to the much debated question of the solubility and transportation of cassiterite. The behavior of mixed sols of silica and tin oxide should be investigated as well as the deposition of wood tin (meta-colloidal SnO_2). Naturally, all these reactions should gradually be established for higher temperatures, say to 70° or 100° C.

Precipitation of Metallic Sulphides.—It has long been known that hydrogen sulphide and alkaline sulphides disperse metallic sulphides in alkaline solutions, and Clarke, Tolman and Menault have extended these experiments to cover phases of secondary sulphide deposition in ores. These experiments should be repeated and extended further to test thoroughly the conditions of stability and precipitation of these sols at temperatures up to 100° C.; also, the action of mixed sulphide sols and the order of

their precipitation; also, the action of silica sols on such dispersed sulphides. To test the possibility of extending these reactions into the realm of higher temperatures and pressures would be the next subject of research. This might be based on the experiments of H. Freeman on the action of sodium sulphide on various melts. It is possible that some of these sols may be found to be more stable than generally realized.

Most of the sulphides are precipitated by H_2S or analogous compounds in colloidal form. Unquestionably this often happens in nature as indicated by the frequent colloform textures of pyrite, marcasite and sphalerite. Valuable experiments have been made by Dr. R. C. Wells on the fractional precipitation of cuprous and ferrous sulphides and they should be extended to cover other common sulphides to ascertain the rate and the order in which precipitation takes place.

Precipitation of Other Salts.—The fractional precipitation of the basic and the normal carbonates, such as those of copper and zinc, is another subject of importance. For instance, malachite and azurite are closely related but malachite is almost always a colloidal precipitate while azurite usually forms in crystals.

During oxidation the oxy-salts usually develop in a certain order, say in case of zinc (*a*) smithsonite, (*b*) calamine, (*c*) hydrozincite, (*d*) willemite. The reason why this happens has not been established. Likewise, the molybdates and vanadates tend to develop in a certain succession for which it may be important to know the reason.

The well-known experiments of E. C. Sullivan on "adsorption" of metallic substances by kaolin, sand, etc., have recently been followed up by a paper in *Zeitschrift für Praktische Geologie,* but these reactions should be further studied and extended.

Separation of Chlorides by Sublimation.

Chlorides escape plentifully in many fumaroles during volcanic eruption. As no doubt similar escape takes place during intrusions and as these chlorides may be carried upward to form ore

deposits it would be of interest to establish if they are given off in any definite order. Many facts relating to this are contained in the chemical and metallurgical literature.

The System Silica-Water-Calcium Carbonate.

No exact work has been carried out to investigate this system which certainly is one of the most important in regard to ore deposits. There is a statement somewhere in the literature that some calcium silicate forms by the action of silica sol on iceland spar. But ordinarily it is assumed that calcium carbonate is replaced by silica at lower temperatures and that the anhydrous calcium silicates, like wollastonite, do not form until temperatures of 400° or 500° are reached. The whole problem of these reactions at higher temperatures and processes is one of the highest importance for the proper understanding of the pyrometasomatic and other high temperature processes. The same applies to magnesium and iron carbonate. Theoretically, a slight pressure equal to the dissociation pressure of CO_2 in $CaCO_3$ should be sufficient to inhibit the reaction. Is this true? This important research would establish valuable datum points of temperature in the formation of ore deposits.

Problems in Solubility.

The solubility of the ordinary sulphides in water at ordinary temperatures has been fairly thoroughly established. What is not known, however, is the action of water at high temperatures on such sulphides both in crystallized form and in the form of colloidal precipitates. This is a very important line of investigagation.

The solubility of certain oxides under similar conditions should also be examined, particularly with reference to magnetite, specularite and cassiterite. Regarding the latter mineral there is room for additional work for there are many controversial points. The action of phosphates on cassiterite, also the action of ferrous salts on the mineral, should be determined.

Another experimental problem is the action of steam on the volatile metallic chlorides.

Still another is the effect of certain organic compounds on the solubility of oxides, carbonates and sulphides.

Problems Regarding Gangue Minerals.

The gangue minerals of metallic ores offer a wide field for synthetic experiments. While quartz, alunite, fluorite and barite have been reproduced, further examinations are needed as to their fields of stability; few high temperature gangue minerals have been reproduced; particular reference is made to sericite, the most common follower of metallic ores, tourmaline, garnet, epidote, axinite, ilvaite, etc. These problems alone contain work of many investigations for a series of years.

The problems of serpentinization, chloritization and dolomitization are merely mentioned here, but in spite of much work already done, experimental investigations are needed. Regarding dolomitization, Dr. Wells suggests the possible reversibility of the following reactions:

$$CaCO_3 + MgSO_4 = MgCa(CO_3)_2 + CaSO_4,$$
$$MgCO_3 + CaSO_4 = MgCa(CO_3)_2 + MgSO_4.$$

Sulphide Melts.

Data relating to the pegmatite deposits are needed but a discussion is here omitted as the Geophysical Laboratory is already engaged in successful work in this direction. There is, however, great need for investigation with the subject of sulphide melts at higher pressures. The behavior of the melts at ordinary pressure is pretty well known through the researches by J. H. L. Vogt, by the Geophysical Laboratory and by various metallurgical work. What is not known, however, is the behavior of melts with various mineralizers such as water, phosphorus, chlorine under heavy pressure. To what extent may the point of fusion be lowered by admixture with such mineralizers, and in how far are they miscible with the sulphide melts? The action of sulphide melts on rocks and the nature of the accompanying replacements are not well known, though the experiments of Stutzer form a beginning of such investigations. Finally, the mode of consolidation of sulphide melts under pressure remains to be examined.

It would be well possible to undertake experiments on mixed sulphide and silicate melts, preferably under pressure, to obtain some clues as to the nature of differentiation in such melts. The experiments of Stansfield have shown that sulphide particles are actually carried up by flotation, buoyed up by gas bubbles.

With a view to determine the mode of origin of dike-like masses of magnetite like those of Kiruna, in Sweden, work should be done on magnetite melts, mixed with apatite and a small amount of silicates, the object being to ascertain what the temperature was at the time of intrusion, assuming that the deposit really is a dike. Some metallurgical data are available, bearing upon this problem.

Magnetite and Specularite.

The system magnetite-specularite-ilmenite has been the subject of considerable work but much still remains to be done in outlining the fields of stability of these minerals. Specularite seems to be formed at low temperatures as well as at high. When we find large masses of specularite in an ore deposit, what does that mean as to the temperature of formation? A study of magnetic ferric oxide is recommended. What is the actual range of stability of magnetite? We know that it forms readily at high temperature but it appears also in certain low temperature forms of metamorphism. The whole relationship of these minerals well merits more study. Incidentally, what is the lowest temperature at which ilmenite may form? Are minerals containing ferrous oxides compatible with pyrite in solution at high temperature?

Unmixing.—The question of unmixing or the separation of a new mineral during the cooling of an older mineral is still more or less unsettled. What are the criteria by which such "unmixing" can be differentiated from ordinary replacement at lower temperatures, and what kind of molecular process is "unmixing"? The fields of metallography and ore deposits here come in contact and it would be highly desirable to obtain a clear statement in how far the principles of metallography apply to ores. Heating, cooling and quenching of mineral mixtures may throw light on this. Some experiments along this line have already

been carried out by Wandke, Schwartz, and Newhouse, relating to changes in the micro structure, say of chalcocite and bornite, by slight heating. A discussion of how replacement acts at high temperatures and whether there is any difference between high temperature and low temperature replacement would be of interest.

Post-hypogene and Pre-supergene Changes in Ores.

There is naturally a considerable interval between the close of the ore formation by hypogene (ascending) agencies and the beginning of attack by surface water. During this interval many interesting things may happen. Recrystallization by pressure may occur as it does in metals and alloys. But even in the absence of pressure, reactions between hypogene minerals may be carried out by the residual moisture and heat in the deposit. Of such nature is probably the development of lead sulphantimonides by reaction between tetrahedrite and galena as investigated by Waldschmidt at the East Hecla mine in the Cœur d'Alene district, Idaho, and at Broken Hill (N. S. W.) by Stillwell. Marcasite and perhaps other minerals accompany this reaction. Probably many other mineral mixtures yield analogous results which are now mostly interpreted as belonging to the later phases of hypogene activity.

A Study of Pseudomorphs.

Pseudomorphs, carefully investigated, give excellent proofs of the transformation of minerals by metasomatism or by other processes. Blum's treatise on pseudomorphs, now about 80 years old, has been most useful to many students, but is now of course entirely out of date. A new volume on this subject from a modern standpoint would prove a great help to students of ore deposition, and the work, while calling for an expert mineralogist, would require no particular and difficult experiments.

Problems of Differentiation of Metallic Substances in Magmas.

The far-reaching questions of the manner in which many metallic and non-metallic substances are set free from intruding

and extruding magmas have not been detailed in this review. The subject is being handled ably by the Geophysical Laboratory in a series of special studies. The problems outlined in these pages refer more particularly to the interpretation of the composition, texture and structure of metallic ores.

CONCLUSIONS.

A long list of problems has been submitted in the previous pages. They are not always presented in logical order for the subjects are closely interwoven and interrelated.

It has certainly been shown that there exists a great need for work in the way of correlation, generalization and physico-chemical studies. We have arrived at a point where more is required than descriptions of individual deposits and districts. There must be coöperation between geologists, and coöperation between geologists on one hand and chemists and physicists on the other hand. Fundamental data are most urgently needed; individual efforts do not suffice. If important advances are to be registered, a more liberal and enlightened attitude must be held by official bodies of investigation and by the metal producing industries. As explained above, the latter have contributed practically nothing to the advancement of this branch of science so essential to their problems.

NATIONAL RESEARCH COUNCIL,
WASHINGTON, D. C.

GEOLOGIC STRUCTURE OF THE CUYUNA IRON DISTRICT, MINNESOTA.

CARL ZAPFFE.

INTRODUCTION.

Not one of the many articles published in the past twenty years pertaining to the Cuyuna iron district has been devoted to the presentation of data relating to intricate structural problems of specific units of the district; nor have these unit structures been used to arrive at a solution of the major structural problems, thereby helping also to account for the puzzling relationship between certain distinctive rock strata in different parts of the district. Of the many things that are detailed herein for the first time, probably the most significant to geologists will be the explanation, first, that there are at least two separate major bands of ore formation and, second, concerning their stratigraphic position with respect to each other.

The earliest geological publications pertaining to the Cuyuna district [1] contain only general statements regarding the probable structure of the whole district, and many of the generalities then set forth have been substantiated by subsequent mining developments. Several years later Harder [2] described certain ore deposits; and then, in 1918, Harder and Johnston,[3] who were en-

[1] Zapffe, Carl, "The Geology of the Cuyuna Iron Ore District," Thesis, University of Wis., 1907; "The Cuyuna Iron Ore District of Minnesota," Brainerd Tribune Supplement, Sept. 2, 1910; "Geology of the Cuyuna Iron Ore District, Minnesota," Amer. Ass'n. Adv. of Science, Dec. meeting, 1910; also *Science*, n. s., vol. 33, page 463, March 18, 1911. Leith, C. K., "Geology of Cuyuna Iron Range, Minnesota," Econ. Geol., vol. 2, pages 145–52, 1907. Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," U. S. Geol. Surv. Mon. 52, pp. 211 to 224; 620 et seq. (Chap. IX, Cuyuna district, etc., Carl Zapffe, joint author), 1911.

[2] Harder, E. C., "Manganiferous Iron Ores of the Cuyuna district, Minnesota," *Trans. Amer. Inst. Min. Eng.*, vol. XLVIII., Oct. meeting, 1917.

[3] Harder, E. C., and Johnston, A. W., Preliminary Report on the Geology of East Central Minnesota. Including the Cuyuna Iron Ore District, Minn. Geol. Surv. Bull. No. 15, 1918; and U. S. Geol. Surv. Bull. 660–A.

gaged by the State and Federal geological surveys, published a preliminary report on the district. The latter [4] wrote that the available information was still too incomplete to attempt to arrange the various beds into stratigraphic successions; as to structures, they [5] quoted the earlier writers and corroborated their statements. Since then no similar comprehensive articles have been published; but two later papers [6] have some bearing on the present topic.

In view of the intensive interest that has been manifested of late by commercial interests in extensions of various known bands of ore formation suitable and alluring for drilling, it seems advisable to describe what the findings of recent years have disclosed in regard to the fundamental geological features. These must be taken into account in explorations, even in the developed areas, and, of course, much more so in outlying and less well known areas.

Of all the Lake Superior iron districts, the Cuyuna district has been given the least critical study and discussion. Even in the following pages the writer finds it necessary to omit reference to many of his investigations of the geology of well-known properties, and, instead to confine himself to a discussion of a few critical places. This study has extended over many years, and has included both good and poor properties, and those that have been developed into mines, as well as those that have only been drilled; but it is impossible to keep abreast with all the newer data, because evidence that comes to light one day, is promptly destroyed by the mining of ore and the caving of the rooms, or by the abandonment of a mine, and is thus lost forever.

[4] *Op. cit.*, p. 2.

[5] *Op. cit.*, p. 111.

[6] Wolff, J. F., "Correlation of Mesabi and Cuyuna Iron Ranges," *Skillings Mining Review*, vol. VII., No. 45, March 29, 1919. Zapffe, Carl, "Stratigraphy and Correlation of the Cuyuna Iron Ore District, Minnesota," *Proc. Lake Sup. Min. Inst.*, vol. XXIV, August, 1925. "Further Data on the Correlation of the Cuyuna Iron-Bearing Member." *Proc. Lake Sup. Min. Inst.*, vol. XXV, August, 1926.

THE PROBLEM.

The geologic structure is not so simple as has been stated in previous writings, although the author [7] wrote as early as 1910 that the rocks were folded into a complex series of northeast-southwest trending anticlines and synclines. Also Harder,[8] as

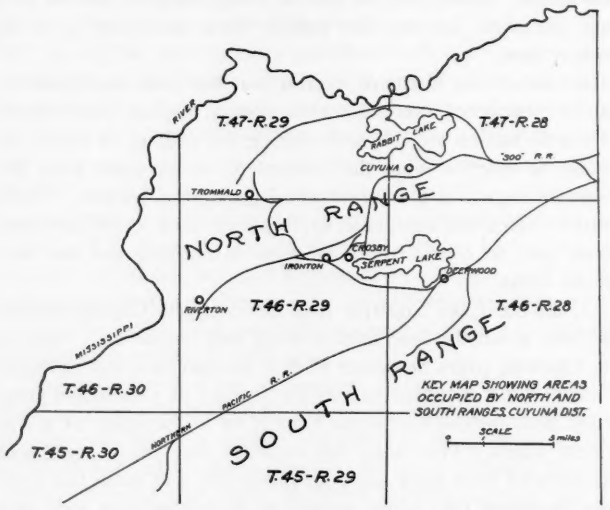

FIG. 1. Key map showing areas occupied by North and South Ranges, Cuyuna District.

late as 1917, wrote that the relation between the separate areas was not then known, but inasmuch as certain ore-bearing belts had characteristic wall rocks, a relation between them might thus be determined; nevertheless, he was inclined to consider all of them parts of a single ore-bearing horizon.

The problem to be discussed may now be presented as three questions: (1) Are the various exposed bands repetitions of a single band due to folding, or are they repetitions of several

[7] Zapffe, Carl, *op. cit.*, Sept. 2, 1910.
[8] Harder, E. C., *op. cit.*, pp. 461, 464.

bands, and if so, how many bands; (2) how far apart are the several bands; and (3) how may the various bands be recognized, and, in the several places, be related to each other.

If it were not for the bands of ore formation, we would know nothing about the Cuyuna district. There is as yet no well-defined stratigraphy. Rocks of Cuyuna type do not outcrop. Magnetic attractions are of some value, and the distant rock outcrops aid in deciphering regional geologic structure.

The discussion of the problem will pertain primarily to a very limited area known locally as the North Range (Fig. 1); even then it will involve primarily the fractional T. 47–R. 29, the north one half of T. 46–R. 29, and the southwest corner of the fractional T. 47–R. 28, although the latter is not so very essential for the proof of the main points offered in this treatise. The North Range contains the producing mines. About four miles southeast is the South Range; it is much larger areally than the North Range, and a little mining has been attempted there. As already remarked, for want of more conclusive data, the various bands in these two areas were formerly considered to be repetitions of the same single band; however, the ore formation was considered to be a horizon consisting of discontinuous overlapping lenses. Thus the two names, North and South Ranges, have always conveyed only a geographical significance.

It shall be the purpose of the author to present evidence that indicates to him that: (1) In the Cuyuna district there are at least two separate bands of ore-formation,—neither being necessarily continuous; (2) the lower band occupies the north part (T. 47–R. 29) of the North Range; (3) the upper band occupies the south part (T. 46–R. 29) of the North Range, and is all that remains of that band (except some of it in T. 47–R. 28, which is also true for the lower band); (4) the bands of the South Range may be extensions and repetitions of the lower band found in T. 47–R. 29, in which case the South Range is identified with the north part of the North Range and geologically is equivalent to a part of the North Range; and there may possibly be even a third band.

For convenience in making the presentation, the North Range is discussed in two portions—T. 47–R. 29 and T. 46–R. 29; and a few comments will be set forth separately about the southwest corner of the adjoining Township 47 in Range 28 (Rabbit Lake Tp.).

REVIEW OF FORMER INTERPRETATIONS.

The South Range was the first ore-bearing area discovered, in 1904. The first ore formation found on the North Range (1905 to 1906) is in T. 47–R. 28, at the site of the Kennedy mine, and virtually no drilling was done on the property after the mine was started, in 1908. Leith[9] then ascribed the occurrence of this formation, and the nearby magnetic lines, as due to folding, ". . . for if it were an independent belt in monoclinal succession, it would imply too great a thickness of formation." It was quite clearly his interpretation that only one band existed in the whole district; and that was the only plausible deduction from the available information.

Harder,[10] in 1917, when mining was already in progress on a large scale, was also of the opinion that there was only one main horizon, but with iron-bearing rocks both above and below it, and interbedded schists within it. This added considerable flexibility.

Harder and Johnston,[11] in 1918, wrote that they found much conflicting data and that it was impossible to work out any definite stratigraphic succession. They said that, "Some geologists believe that probably the different bands of iron-bearing rock of the North Range may be referred to a single layer, but that the bands in the South Range represent a different and probably higher stratigraphic horizon." However, they dismissed the problem by saying: "It is, therefore, more reasonable for the present to assume that only one main iron-bearing horizon exists in the Cuyuna district." Cheney,[12] in 1915, made an interpreta-

[9] Leith, C. K., "Geology of Cuyuna Iron Range, Minnesota," ECON. GEOL., vol. 2, No. 2, pp. 145–152, 1907.

[10] *Op. cit.*, pp. 458–459.

[11] *Op. cit.*, pp. 113–114.

[12] Cheney, C. A., Jr., "Structure of the Cuyuna Iron Ore District of Minnesota," *Eng. and Min. Jour.*, vol. 99, pp. 1113–1115, June 26, 1915.

tion of the rock structure on the same supposition, using the magnetic lines known at that time and deliberately joining all of them at their ends, although in the field the magnetic data did not show such connections.

Wolff,[13] in 1919, stated that the ores lay in one band of formation but occurred, as in the Mesabi formation, at four different horizons within it, each horizon being characterized by lithologic differences. All of the four horizons, he clearly shows, were not present in any single deposit or even in several adjacent deposits combined. The existing mines were grouped and assigned to these four horizons. That resulted as follows: Rowe and Maroco deposits in the fourth or lowest horizon; Croft, Meacham and South Thompson in the third or next higher horizon; part of the Louise, part of the Hopkins, and all of the Algoma, Ferro, Merritt and Clark still higher or in the second horizon; and at the top were placed the Sagamore, Portsmouth, Sultana, Milford and parts of the Mahnomen, Hopkins and Louise. Wolff said "... it was possible to establish (this) definitely, without question." To those familiar with the location of these various properties, some very unusual and astonishing associations may be detected in this grouping.

In 1925, Wolff [14] stated that the South Range was of Upper Huronion age and the North Range of Middle Huronion age. A few months later,[15] he added to his Upper Huronion, the Croft, Meacham, South Thompson, Ironton and Bonnie Belle deposits of the North Range, which deposits he formerly assigned to his third layer. Thus his third layer vanished. These mines, it should be noted, are the southernmost deposits of the North Range and are within a few hundred feet of their neighbors to the north. He separated them because they lacked the lithological similarities required in his scheme. In 1927, Wolff [16] wrote, "Only the Rowe, Maroco, Merritt, Joan No. 4, Ferro, Algoma

[13] Wolff, J. F., "Correlation of Mesabi and Cuyuna Iron Ranges," *Skillings Mining Review*, vol. VII., No. 45, March 29, 1919.

[14] Wolff, J. F., oral communication, Geological Conference, Madison, Wis.

[15] *Ibid.*, oral communication, Crosby, Minn.

[16] *Ibid.*, written communication, May 2, 1927.

and parts of the Louise, Joan No. 1 and Mangan No. 1 are in the Mesabi formation." The remainder he considered to be in a horizon of which there is today no equivalent in the Mesabi district, presumably, he said, having been eroded there. Wolff has, therefore, adhered to the idea of two separate bands but he has successively whittled down that one which he classed as the lower band and thought comparable to the Mesabi formation.

Van Hise and Leith [17] and Zapffe,[18] in 1911, stated that due to the lack of exploration at that date it was difficult to tell to what extent the parallel lenses were independent at different horizons and to what extent they might be duplications by folding. They were assigned as occurring in the Virginia slate, which, in the Mesabi district, overlies the Biwabik iron-bearing member of the Mesabi series.

The reviews given above show how impossible it was in earlier years to arrive at definite correlations. Some of the writers, it is clear, have seen much evidence but appear to have been doubtful about applying it and offering a new interpretation of the structure; though the one who did depart from the first ideas offered, modified his views in such quick succession that they have become unusable.

STRUCTURAL FEATURES.

Shapes and Strikes.—With only few exceptions, the outlines of ore deposits at the erosion surface are lens-shaped, and even if irregular they strike N.E.–S.W.; but the exceptions are, indeed, of great significance, because it is the structure of the beds that gives rise to the shape and strike of the deposits, and these exceptions are perhaps in each place a key that has never before been used to solve major structural problems.

Dips and Folds.—It was a coincidence that most of the earlier drilling was in ore bodies and lean formations that were unaffected by local folds; and the preponderance of steep southeast

[17] Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," U. S. Geol. Sur. Mon. 52, p. 212 et seq., 1911.

[18] Zapffe, Carl, as joint author of Chapter IX., U. S. G. S. Mon. 52, p. 217. 1911.

or vertical dips, with only few dips to the northwest influenced the view that monoclinal attitude was general, except that each band might be duplicated in parallel succession by rather regular and open folding. Flat dips were considered to be the result of slumping or small drags. It is apparent to anyone that from drilling alone a closely pressed inclined fold can seldom be recognized in any single property. Since mines have been developed, numerous structure have been exposed, and we now know that many kinds of folds are present; apparent simple monoclinal structures are in reality closely pressed folds or twisted, contorted masses, whose extensions may be traced into adjoining properties. This is especially true for the area in T. 46–R. 29.

Pitch.—For many years it was thought that the controlling folds pitched northeastward, but it is now evident that in some restricted areas the pitch of numerous folds is southwest. A full appreciation of the pitch and the folds reconciles many formerly puzzling features.

Axes.—Too much regularity and simplicity has been assumed for the folding. The courses of the axes of many folds are sinuous; axes wind in and out of ore-bodies and into the enclosing lean formation and the bordering green wall-rocks. This fact, when recognized, eliminates many problems and simplifies others.

Faults.—From drill data alone it has so far been impossible to discern faults or faulted ground. The shearing, twisting, and stretching observed might lead one to suspect the presence of faults, but such distortions also influence or determine the kind of faulting, a feature that has not always been given proper consideration. To date, only one fault has been definitely recognized in a mine. This is in the Milford mine, and it seems to be of only local consequence. Rundle [19] believes that a small fault has been detected on the 333-foot level of the Croft mine.

Horizon Markers.—That the ore-formation is the one and only outstanding horizon marker has already been stated. Harder [20] stated that possibly locally characteristic wall rocks he observed

[19] Rundle, T. F., oral communication.

[20] *Op. cit.*, p. 464.

might be utilized to correlate certain of the ore-formation bands. Much has been written about the manganiferous ores in the district, but here it need only be pointed out that it was recognized [21] that in properties containing both iron ore and manganiferous iron ores, the latter were confined in some mines to footwall beds, in others, to the hanging wall, and in still others, to the middle or the ends of the ore deposits. This distribution has a structural significance. The dominant feature of the ore-bearing area in T. 46–R. 29 is the complexity of the folding, giving rise to many repetitions of the same beds; and the presence of a manganiferous horizon at the base of this formation, as may now be postulated, elevated by folding and exposed by erosion, results in a re-occurrence of manganiferous layers in the different places named with respect to the outlines of the whole ore deposit. This layer, like the one producing the iron ores, is not everywhere concentrated to ore; it also varies in thickness to the extent of being absent for long distances. This layer is an excellent horizon marker, and it has been made use of in many interpretations in the present study.

LITHOLOGIC FEATURES.

Even the casual observer is impressed with the dissimilar lithology of the ore formation in certain unit areas. It is evident that for such units hard and fast rules can not be prescribed, but the differences taken as a whole have become more and more significant as time has gone on.

The magnetic lines or belts of T. 47–R. 29 and those of the South Range are much alike, although they are seven miles apart. In contrast, in the two adjoining areas, T. 47–R. 29 and T. 46–R. 29, they have little similarity. Magnetic slates are abundant everywhere in the ore formation bands in Tp. 47, though in Tp. 46 they are lacking in most places. Oxidation has been much more extensive in Tp. 46 than elsewhere; but we may attach some value to the fact that the limitation of the oxidation in Tp. 47 and in the South Range are so similar in those two areas and also so

[21] Zapffe, Carl, "Manganiferous Iron Ore of Cuyuna District, Minnesota," *Trans. Amer. Inst. Min. Eng.*, February meeting, 1925.

much less than in Tp. 46. This difference in extent of oxidation may really be due more to original lithologic differences than to subsequent conditions during the period of ore concentration. There is actually nothing discernible today on which to base the idea that topographic or meteorologic conditions favored uniformly deeper concentration in Tp. 46 than elsewhere.

These magnetic slates grade into rocks that resemble the "green schist," which invariably comprises the wall rocks. The ore formation in T. 46–R. 29, however, with its paucity of magnetic slates, has marked and readily recognized margins. This is a striking feature.

Every deposit in Tp. 47 except the Milford is of the black-ore type of manganiferous ore, which term signifies that the ore is low in phosphorus and high in manganese and silica, as well as being dark brown to black in color. Only very little iron ore is associated with the manganiferous ore. The unoxidized magnetic slate invariably contains 6 or 7 per cent. or more of manganese.

In contrast to this, in Tp. 46 iron is the dominant ore, although the manganiferous ore may at present be receiving greater attention.[22] These manganiferous ores in Tp. 46 are preponderantly of the brown-ore type, which term signifies that the ore is high in phosphorus and low in silica, just the reverse of the composition of the black ore. The color is light brown. The associated iron ores are, on the other hand, reddish in color, preponderantly low to medium in phosphorus content and high in silica, and the manganese is negligible.

The formation of the South Range is about as thick as that in Tp. 47, where no folding has occurred, and the two magnetic formations have similar lithological characteristics. The South Range ores are dark in color, brown to black; but thus far manganiferous ore in quantity has been found in only a few places. The iron ores commonly contain about 1 per cent. of manganese. The phosphorus is higher than that of most of the ores in Tp.

[22] The Sagamore deposit, in Sec. 19, is not considered to belong to the ore-bearing horizon or band on which all the other ore-properties in the north half of this township are situated.

46; and although the iron-content may be less, the silica is always low. In most respects these iron ores are very unlike those of Tp. 46. A comparison of lithologic similarities is more easily made between the South Range and Tp. 47 than with any of the other sub-divisions. In a distance of seven miles across country, and more along the dip, it is not assuming too much to consider that manganese- and phosphorus-characteristics in a formation may change although other things remain much the same.

THE MANGANIFEROUS HORIZONS.

A careful study of the properties drilled, as well as the mines developed, discloses an important layer of manganiferous material at the base of the formation in parts of Tp. 46, but it is neither continuous nor uniform in thickness and in some places contains non-manganiferous layers. Similarly, the upper portion or iron horizon contains here and there small bands or masses of manganiferous material, but these are of very little value or stratigraphic significance. If one recognizes these small irregularities; and if one bears in mind that each property,[23] or each small group of properties, is situated on one or more folds, which may run straight or be bent, be open or closed, symmetrical or overturned, irregular as to original elevation or subsequent erosion, it is now not difficult to solve or explain the structure of nearly every deposit or property and assign it to its proper place in the major structure of this area. The many folds which in single properties have baffled some operators, have only helped to explain what elsewhere nearby seemed to be incongruities. The recognition of this manganiferous horizon at the base has helped greatly.

In Tp. 47 the largest part of the formation is manganiferous. Where a non-manganiferous portion occurs in large amount, it constitutes commonly the upper part. But one also finds thin bands of each kind in inverse relationship. Concentration has, as it appears thus far, been facilitated in the central part of the whole thickness, and sometimes this makes the stratigraphic relationship between the manganiferous and non-manganiferous ores appear different than stated.

[23] Each is a 40-acre sub-division.

MAJOR STRUCTURE.

The east portion of the Cuyuna district lies between the Giant Range granite of the Mesabi district on the north and a less well-defined ridge of granite and gneiss on the south, passing south of Mille Lacs Lake. This intervening area is a huge basin. Here, as elsewhere in the whole Lake Superior region, the preponderance of strikes in the major and minor structures is N.E.–S.W., meaning that deformational movements during the different geologic periods have been amazingly uniform in direction. This reduces the hazards in making deductions.

That the Mesabi formations marked the north limb of this particular basin, was quite obvious for a long time and has never been doubted; as to the rest, the following statements were offered. Zapffe,[24] in 1907, described the structure of this intermediate area, showing it to be a large synclinorium lying north of the major axis of the Lake Superior synclinorium. Van Hise and Leith,[25] in 1911, refer to it as a minor synclinal fold in the main Lake Superior synclinorium, comparable to the one in the Marquette, Menominee and other districts. Harder and Johnston [26] considered the Cuyuna district to be in the basin lying north of the axis of the major Lake Superior synclinorium, the axis of the latter being marked by the ridge of granitic intrusions south of Mille Lacs Lake.

In restricting the area to that space in which the ore-bearing bands occur, one must be more specific. Van Hise and Leith,[27] in discussing the North and South Range areas in 1911, said the facts may indicate either a northeast pitching anticlinorium or a southwest pitching synclinorium, but regarded the former more probable. Harder,[28] in 1917, presented a hypothetical cross-section across Tps. 46 and 47, R. 29, which is reproduced herein as Fig. 2. It shows two anticlinoria, one in each township, with

[24] Zapffe, Carl, "Geology of the Cuyuna Iron Ore District, Minn.," Thesis Univ. of Wis., 1907; Amer. Ass'n. Adv. of Science, Dec. meeting, 1910.

[25] *Op. cit.*, p. 623.

[26] *Op. cit.*, p. 112.

[27] *Op. cit.*, p. 213.

[28] *Op. cit.*, p. 464.

a small synclinorium between them. The north one is given a higher elevation for its hypothetical crest. There are no distinctive beds depicted to show the synclinorium, and it may not be

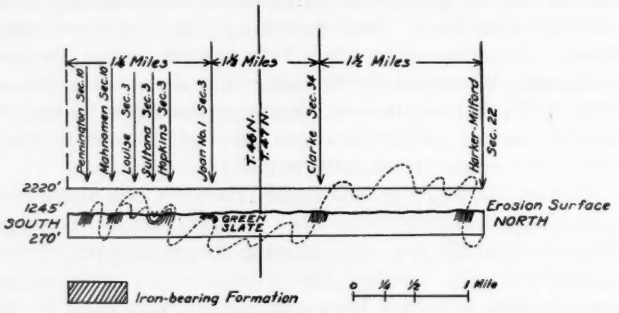

FIG. 2. Geologic Section across the North Range, Cuyuna District, showing the possible structure of the rocks (after E. C. Harder).

present; it could have been surmised only, perhaps, by a few dips on explored lands one mile apart, and these lands happen to be without any indication of continuity of the same strata between them. In view of Harder's interpretation of the structure for the larger area, it follows that this portion of the larger Cuyuna area is part of the crumpled north limb of a large synclinorium; and that for the restricted portion, or ore-bearing areas, in these two townships, one may deduce that Harder considered both townships to be anticlinal portions on this limb. Harder's section, however, is not complete on the south edge. Harder and Johnston,[29] in 1918, made a statement similar to the one made by Van Hise and Leith, and in addition commented on the diversity of the pitches of folds in local areas. Wolff [30] said that the general structure of the North Range was a northeast pitching synclinorium, containing closely folded synclines and anticlines; but he presented no details or explanations to substantiate his conclusions.

[29] *Op. cit.*

[30] *Op. cit.*, p. 4.

That the Cuyuna district, considered in a larger sense, is a portion of the north limb of a large synclinorium is hardly to be questioned; its areal distribution suggests it, and the general type of folding present locally in the ore-producing areas supports the view as well as fixes the position of the restricted area. Idealized in a diagram, which has been widely used, the space marked in Fig. 3 shows very clearly where the Cuyuna is believed to be, and

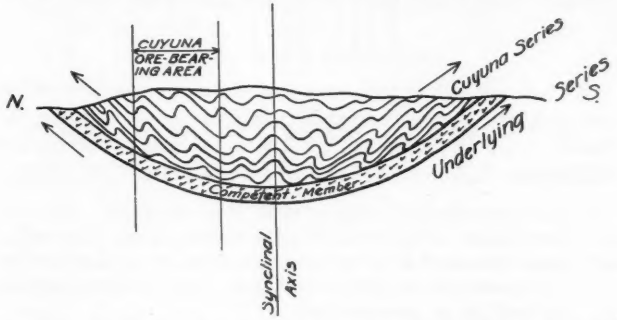

FIG. 3. Idealized sketch to show character of folding in a series like Cuyuna series; also place in synclinorium occupied by the Cuyuna ore-bearing area.

why. . Leith [31] says that the position of major folds is inferred from the differential movement indicated by the minor folds, and that the major fold may in turn be one of a series of folds related to a still larger fold, and that this is one of the most fundamental principles in the field study of structure. To that statement may be added that probably in no district in the Lake Superior region can this statement be applied to better advantage than in the Cuyuna district, and Fig. 3 is offered as an explanation for the preponderance of southeast dips in the Cuyuna area.

It is obvious that the Cuyuna ore-formation bands have been revealed at the surface by erosion of anticlines; nevertheless, in the whole Cuyuna district there must be synclines, and in certain areas they are the dominant local structural features. The rela-

[31] Leith, C. K., "Structural Geology," p. 115, Henry Holt & Co., 1913.

tionship between such different local folds in unit areas is what the writer is endeavoring to clarify. He [32] has already recorded his belief that the Cuyuna ore-formations are not the extension of the Biwabik formation of the Mesabi district and that they are not basal to the Cuyuna series; consequently, the folds that elevated the ore-formation bands need not have been high; but this elevation was of varying degrees in different places, as was also depth of erosion, and these things had a combined result.

PROPOSED INTERPRETATION.

With the preceding comments and explanations before us, we may now state succinctly what the principal structures in the ore-bearing areas in Tp. 46 and 47, R. 29, are believed to be, and what certain local features are believed to signify.

1. There are at least two principal bands of ore formation. The lower band appears in Tp. 47 and the upper band in Tp. 46. The vertical space between them is not uniform but may be as much as 2500 feet in at least one place if that intervening area is not affected by local but yet unknown folds.
2. The major feature in the ore-producing area of Tp. 47 is anticlinal, with few subordinate folds.
3. The major feature in Tp. 46 is synclinal, the ore formation here being considerably crumpled into smaller synclines and anticlines.
4. The north limb of the syncline of Tp. 46 rests on the south limb of the anticline in Tp. 47.
5. A dome, with a center in the northeast portion of T. 46, R. 29, followed by erosion to base-level, has made the syncline in this township narrow in the eastern part and makes the north limb here occur far southward from its otherwise normal position.
6. The numerous southwest pitches in Tp. 46 have important local significance; otherwise, the pitch of the major structure is northeast.
7. A second anticlinal structure seems a logical inference, being indicated by the Sagamore mine area in Sec. 19, T. 46, R. 29, and Sec. 24, T. 46–R. 30, on which the south limb of the Tp. 46 syncline rests.

[32] *Op. cit., Proc. Lake Sup. Min. Inst.*, vols. XXIV. and XXV. *Op. cit.*, U. S. G. S. Mon. 52, Chap. IX.

A typical N.W.–S.E. cross-section through the main ore-producing areas of the two townships where most of the mines occur, depicting at the same time the essentials of the various larger folds involved rather than local details, is shown in Fig. 4. Sec-

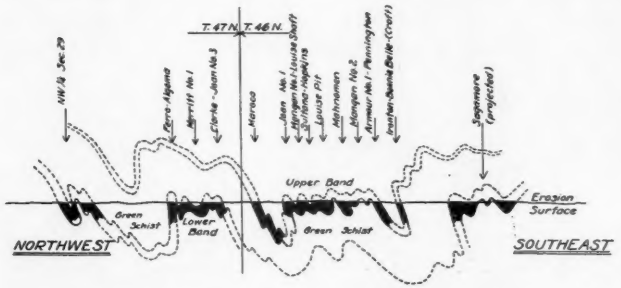

FIG. 4. Geologic section from N.W. Cor. Sec. 29, T. 47 N.–R. 29 W. to S¼ Cor. Sec. 11, T. 46 N.–R. 29 W., showing the probable structure and relation between an upper and lower ore formation.

tions made only a few miles east or west of it (see Figs. 9 and 11) show quite different spacings and different minor folds; the easterly section emphasizes the anticlinal structure to the north in Tp. 47, while the section to the west would show more clearly the synclinal structure in Tp. 46. The reader might compare the section shown in Fig. 4 with the one shown in Fig. 2, which presents Harder's interpretation; but Harder's section was a N.–S. section, therefore the north end of it, where the anticlinorium in T. 47–R. 29 is well shown, can not appear like the north end of the one shown in Fig. 4. The writer agrees fully with Harder's representation of that part which is in Tp. 47.

STRUCTURE IN T. 47 N.–R. 29 W.

It is not essential to consider the details of the areas north or west of this township, because they contain no mines and have been drilled sparingly. Fig. 5 shows the distribution of ore bands, the numbers being added for convenience. It is not yet

possible to show here many deviations due to local folds, but they are undoubtedly more numerous than indicated. Band No. 1 has been drilled for nearly its full length but supports no mines. It is very wide in places and some folding may be detected. The thickness of the ore formation in the Cuyuna district is normally 200 to 400 feet where the structure is simple. It has been the writer's experience that where greater thicknesses have been en-

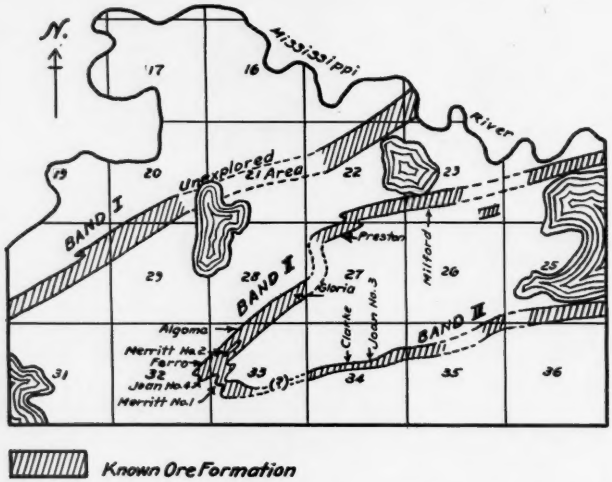

FIG. 5. Sketch showing bands of ore formation in T. 47 N.–R. 29 W. Dotted lines are assumptions based on magnetic surveys.

countered by drilling, subsequent mining operations have disclosed that intricate folding is present. In fact, the folding is far more intricate than may appear from drill records only, or from these descriptions. Band No. II. has been drilled for nearly its full length and has had seven operating mines, mostly very small ones, but they have yielded much information about the folding. Band No. III. has been only partly explored; and although two mines were started (Clarke and Joan No. 3), no information regarding the formations has been gained from them.

The areal distribution of Bands II. and III., and other facts, suggest an anticlinal structure. This was also Harder's interpretation (see Fig. 2.). Harder and Johnston,[33] commented on the great width of formation on the Algoma property, in Sec. 33, where they measured 1000 feet. They said it varied in character, was distinctly manganiferous, contained three or four lenses of ore, and dipped steeply to the south and also vertically In contrast, in writing about the Ferro mine, which is less than one half mile southwest, Harder [34] commented on the comparatively narrow zone here, and found the dips to be steeply south to vertical. A few hundred feet southwest of the Ferro is the Joan No. 4, a very small mine at the end of the belt, where the dips were vertical and northward. Although the two Merritt mines were then in operation, nothing was written about them by these authors. A study of all this work shows conclusively that an anticline passes through these various properties and it accounts for the great width of formation at the Algoma mine. Furthermore, the south limb, or probably the crest of the major anticline, has here several distinct synclines on it, pitching northeast; the largest of these contains the principal orebody constituting the Merritt No. 1 mine. The south limb of this syncline folds over again, and apparently is cross-buckled.

Fig. 6 shows in plan and cross-section a little of the detail in this interesting area.

Similar foldings occur elsewhere in this township, but the lack of exposures by mining renders precise representation unwarranted. However, based on past experience, a great width of formation, even with parallel dips, at once suggests folding. Some evidence is also at hand that there is much folding in the green-schist area between the limbs where the ore bands are now depicted widely separated.

At the Merritt property it is certain that the formation is only 300 to 350 feet thick, and it contains a thick manganiferous member in the lower part and a thinner non-manganiferous phase near the top. Were the folds not discernible here, upon platting

[33] *Op. cit.*, p. 138.
[34] *Op. cit.*, p. 472.

this drilling, one would undoubtedly report a thickness of between 600 and 1,000 feet.

The Preston property, in Sec. 27, and lands eastward, in Sec. 22, constitute a mile stretch that shows much folding, but is not yet clearly defined; apparently it contains some drag folds of good size. The Milford mine deposit, in Sec. 23, shows a N.W.–S.E.

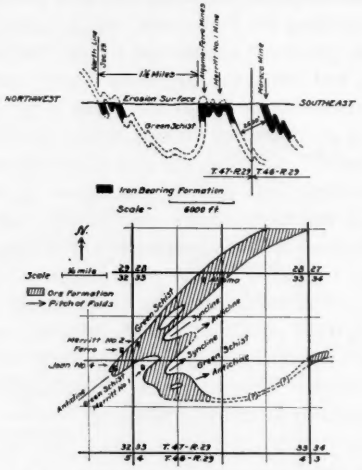

FIG. 6. Cross section and plan of southwest part of T. 47 N.–R. 29 W.

fault which has dislocated the ore formation. The Clarke and Joan No. 3 prospects, in Sec. 34, have lately been redrilled and here the formation appears to be the south limb, the same as found further east in T. 47–R. 28, of the large anticline.

Where Band No. III. may reappear to the south remains a matter of speculation. It is believed that the Sagamore deposit in Sec. 19, 46–29, 2½ miles south, represents it, and it is not at all unlikely that the South Range may also be its continuation. For the present, the writer inclines to both these views. Northwardly, Band No. 1. may be represented by unidentified bands of rock which were originally progressively much lower in iron-

content and magnetite; or it may have its equivalents in those distant bands on which some exploration has been conducted sporadically and that still appear to be without linear connections.

STRUCTURES IN T. 46 N.–R. 29 W.

The distribution in plan of the bands of ore formation now known in Township 46, Range 29, is shown in Fig. 7. The figure is intended to show primarily the general outline rather than details of the ore-formation areas; each land section and

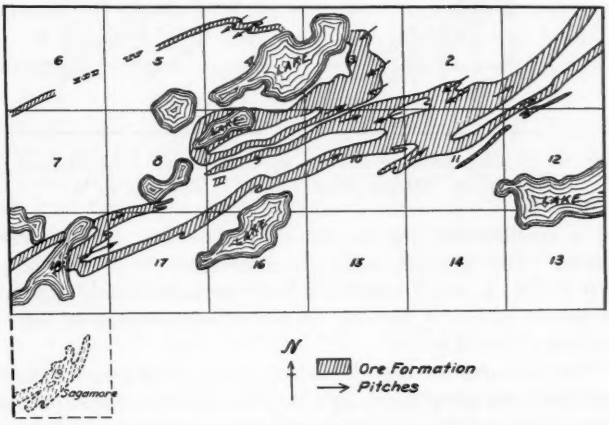

FIG. 7 Sketch map showing the distribution in plan of the ore formation in T. 46 N.–R. 29 W.

usually each forty-acre tract, has its own peculiar geologic structure. Each such unit forms an essential part of a more complex and a larger structure, therefore, some details of the geology of this township may be given.

In Fig. 8, "A" is a cross-section (looking east) of a southward dipping band of ore formation which has several small folds on it. If this band is tilted sideways and upward toward the east (or northeast) the course of the band at the erosion surface is in plan as shown in "B." Beds at points *A*, *B* and *C* will

correspond with beds at points *AA, BB* and *CC* respectively; what we see now in plan is a bevelled edge (at a small angle) down the dip rather than what was the strike on the horizontal plane, and each of these smaller folds seen on the dip of the single band shown in cross-section will appear in plan as synclines having a westward or southwestward pitch. If "A" is the north limb

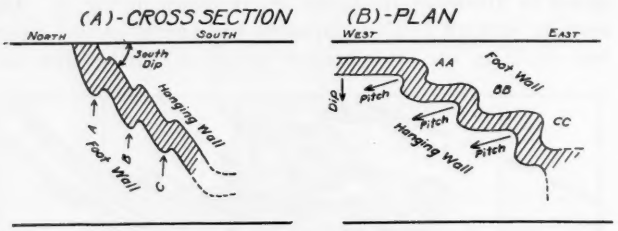

FIG. 8. Diagram showing in cross-section and plan a folded band of formation. Maroco Mine, Sec. 4, T. 46 N.–R. 29 W.

of a synclinorium, the development shown in "B" is accentuated. This is exactly what one observes on the Maroco property in Sec. 4; and it explains also the serrated easterly edge encountered in Sec. 3 and the northerly serrated edge in Sec. 2 adjoining (see Fig. 7).

The numerous ore deposits in Secs. 2 and 3 are preponderantly synclinal, and along this margin they show the southwest pitches, just as seen in the synclines at the Maroco property in Sec. 4. These S.W.-pitches have been noted by many observers, and have been casually referred to by them as the result of a cross-buckle in the middle of the township. This cross-buckle has never been explained. The writer believes that the following explanation will account for more structural features observed here than any other explanation he has considered, although it is not to be inferred that only a single movement is involved.

In Secs. 4, 5 and 6 (Fig. 7), the ore bands appear straight; in Sec. 1, and beyond in Secs. 6 and 31 (not shown in Fig. 7) is a similar feature, but here the formation tends to swing more sharply northeastwardly, and then again courses eastwardly.

It seems probable that some force has dislocated the formation and given rise to the curved distribution noted in Secs. 1, 2 and 3. This force, apparently, was a doming one, with a center in the north part of Sec. 2. Southward and westward it raised the crenulated basin, giving rise to southwest pitches; southeastward and northeastward it gave rise to northeastward pitches, not so numerously recorded here, but just as evident and significant. The north ore band in Sec. 1 shows close strike folds which give it width. The south band in Sec. 1 is undistorted. Furthermore, at the Kennedy property in Sec. 30, 47–28, at the northeast, the normal spacing with respects to the underlying or Tp. 47–R. 29 band, is again evident. This area will be described more fully in following pages. South to southeast of the dome, the crenulations that westwardly give rise to separate basins, are folds in the narrow ore bands parallel with the general strike of the formation. Beveling the dome, by erosion, would obviously remove much formation above it and bring the new margin of the domed ore-formation southward in Sec. 2, westward in Sec. 3, and eastward in Sec. 1, as now observed.

One may ask whether similar contortions and dislocations occur on the north side of this dome. Referring to Fig. 5, this dome would occupy nearly all of Sec. 36, much of Sec. 35 and just a little of the S.E. quarter of Sec. 34. Though one sees in Tp. 47 slight irregularities in the strike and dip, they may or may not be due to this doming. But it may be pointed out that the alignment between the ore bands in Secs. 4, 5 and 6, T. 46–R. 29, on the west, and the corresponding bands at the Kennedy mine in Secs. 29 and 30, T. 47–R. 28, on the east, indicate that this dome is almost wholly in the area formerly covered by the T. 46-formation, and that the north rim of the dome corresponds fairly closely with the course that the north edge of the formation would have occupied, had it not been domed and eroded. The domed area is ellipsoidal to oval in shape, with its blunt end to the southwest, in Secs. 2 and 3. It is believed to have been only a low dome; consequently only the upper ore layer would be seen, and that is the formation in Tp. 46.

As the formation in the central area of Tp. 46 had a zone of

manganiferous formation at or near the base and was a little thicker here than elsewhere, it has given rise here to a larger number of manganiferous ore mines, because of the broad folding and wrinkling. Each mine is identified with one or a group of these small folds.

Wolff [35] was inclined to think that these manganiferous mines were in various horizons of the same band of formation which occurs northward in T. 47–R. 29. Harder [36] considered these mines and formation, in Secs. 3, 4 and 9, T. 46–R. 29, to be in the same horizon, but concluded that they were unlike those in T. 47–R. 29; the present writer is of the same opinion. The ores are preponderantly brown manganiferous ores. The small amount of black ore found in this very small area is a local feature. On the other hand, all the structural features of these two Tps. 46 and 47 are in discord if one considers the bands identical.

The Maroco mine in Sec. 4 and the Merritt mine in Sec. 33, are spaced about 2,500 feet apart. It is not known if there are any folds in the intervening green schist that would lessen the thickness. The vertical distance between the two bands ought not to exceed 2,500 feet, and it may be less. A similar distance separates the ore band of the Rowe mine (Sec. 18, 46–29) and the ore band of the Sagamore deposit (Sec. 19) south of it. This may be only a coincidence, but it may also favor the assigning of the formation of the Sagamore area to the lower, or Tp. 47–R. 29 band.

The doming and the subsequent erosion have caused a large area in parts of Secs. 1, 2 and 3 in Tp. 46, and Secs. 34, 35 and 36 in Tp. 47, to be free from ore formation. As one goes away from this dome, the distribution of the formation is found to be more regular and, therefore, less from normal. In one area in this township the width of the exposure is due to broad shallow folds, and in other places it is due to duplication and repetition of beds by close folding. It seems that the doming in this one place accounts for most of the minor structural irregularities.

[35] Wolff, J. F., *op. cit.*
[36] Harder, E. C., *op. cit.*, p. 462.

Another interesting area, from a structural standpoint, is the extreme western part of Tp. 46. The best explored part is in Sec. 18, and parts of Secs. 17 and 8 adjoining it on the east. Here, and elsewhere to the east, are good data pertaining to the upper band and particularly the south limb of the synclinorium in this township. The abandoned Rowe mine is in Sec. 18. In the pit were confusing strikes and dips, due to twisted folds that formed a tightly compressed syncline on the east end, resembling monoclinal strata, and an open synclinal fold on the west end,

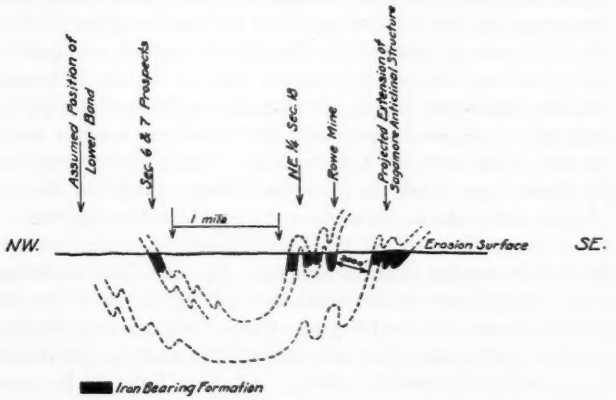

FIG. 9. An idealized cross-section through the westerly portion of the T. 46 N.–R. 29 W. synclinorium.

the north limb here turning over northward into an anticline. All folds have sinuous courses. The erosion surface is irregular. Areas of concentration were irregular in shape and somewhat disconnected; they constituted the ore pockets. Fortunately, Harder and Johnston [37] have preserved much of the data relating to strikes and dips of the beds seen in the pit by recording them on a plane-table map. Due to a northeast pitch, the Rowe syncline presumably terminates to the west at about the shore of Little Rabbit Lake, but the beds are repeated to the north, in the

[37] *Op. cit.*, p. 139.

N.E. quarter of Sec. 18, by several folds. In two places north of the Rowe mine the beds continue southwestward along the strike; the known distribution of ore bands leaves little doubt that between Sec. 18 on the south and the Maroco deposit in Secs. 4 and 5 on the north a synclinal structure exists. An idealized cross-section through this area is shown in Fig. 9. It is clear that the Rowe syncline is really a relatively small structural detail in the whole problem, but it makes evident the up-turned south limb of this synclinorium.

The ores, and the lean formation, of the Maroco and Rowe properties are much alike, and their similarities differ from all other Cuyuna properties. In the Maroco deposit are spots of manganiferous formation along the base of the ore formation, and the same is true in Sec. 18, especially on the south wall at the east end of the Rowe pit where the overturned syncline brings up such a phase in the hanging wall. The wash-ore type and the cherty type of ore are abundant in both, and unlike the ores of most other mines. Washers were used at both properties.

Section 19, T. 46 N.–R. 29 W.—This section of land contains the well-known but isolated Sagamore deposit. The ore-formation, however, extends westward into Sec. 24, T. 46–R. 30, and touches eleven or twelve forty-acre tracts. It has a very irregular outline. As no more than one fifth of this immense ore deposit is exposed by the present open-pit, only very little can be determined about the complete structure. Its true place in the Cuyuna series has always been a baffling question, and much remains conjectural. The formation has not quite the same linear alignment (see Fig. 7) as the ore deposits just discussed, north of it; and there are some things which may justify separating it from the two horizons thus far described.

The north end of this ore-bearing area lies approximately one half mile south of the Rowe deposit, but toward the southwest the distance between the two increases rapidly. The outline of the ore formation is irregular, especially along the northwest side. The southwest end has not been fully outlined by drilling; there, the ore is poorer and the formation is highly irregular. The exposed formation may be likened to the letter "A" whose apex

points N.E. The central portion, between the two legs, is unquestionably the top of an anticline. Where remnants of formation remain on the crest of the fold, suggesting the bar in the letter "A," they show evidence of being crenulations; and, similarly, the limbs show substantial minor folds. It seems that the bulk of the ores rest principally in these minor synclines on the two limbs of the anticline. At the north end, due to the pitch and shallow infolding, the west limb has been eroded further to the south than the east limb. Unless the whole formation and all of the many secondary or small folds in it are taken into consideration, one might be led to say that the distribution of the ores shows a synclinal structure for this area. It does, for portions of it, but it is not true for the whole.

This major anticlinal structure therefore shows that this area cannot be an extension of the Rowe deposit, which is definitely synclinal on its southernmost border. Also, the formations exposed at the Rowe are decidedly non-manganiferous (except as to small special spots) and are very siliceous, whereas the Sagamore formation is manganiferous and devoid of similar siliceous material. Such a strong contrast and in so short a distance is noteworthy; consequently, it would seem that the Sagamore formation is probably the T. 47–R. 29 band brought to the surface by upfolding, that formation being also preponderantly manganiferous.

Unlike the more common black ore of Tp. 47, the Sagamore ore is brown ore, like the Milford ore in Sec. 23, Tp. 47; so it is possible to correlate the Sagamore formation on lithologic grounds with the lower band, found in T. 47–R. 29, even though the ores there are otherwise dominantly of the black-ore type. While the Sagamore ore is to a certain extent like some of the high-phosphorus low-silica ores found easterly in the upper band, in T. 46–R. 29, the similarity is not so apparent; the differences prevent correlating them.

If, as has already been advanced, the bands of the South Range might perhaps be correlated with those of T. 47–R. 29, it may well be that the Sagamore area represents one intermediate phase that would supply a lithologic link between the bands of the South

Range and those of T. 47–R. 29, introducing here the high-phosphorus low-silica characteristics so conspicuous in South Range ores. The drilling on the Sagamore property showed much formation resembling the so-called magnetic slate, being gradations to the non-magnetic slates; this type of rock has invariably been less evident in ore deposits elsewhere in Tp. 46, but has been very conspicuous in the two other areas named.

Being so close to the siliceous iron ore of the Rowe deposit, which also resembles the Maroco ore two miles northward, it seems unreasonable to associate the Sagamore formation with the Rowe formation, for it would mean that in the short space of about 3000 feet the Rowe formation had been completely transformed from a siliceous, non-manganiferous iron-ore formation to the manganiferous ore formation of the Sagamore. Such a correlation seems so impossible that one must accept either that the Sagamore deposit is in the 47–29 band, lying below the 46–29 band, or else that it is in a class by itself, constituting a separate band, and is an orphan.

T. 47 N.–R. 28 W.—In the vicinity of Cuyuna village, in T. 47 N.–R. 28 W., is an area south of Rabbit Lake comprising Secs. 29, 30, 31 and 32, in which the geologic structure has long been a puzzle. Many diverse views have been offered for the geology at the Kennedy mine. This mine (now flooded) which includes several subdivisions in Secs. 29 and 30, was the first mine opened in the Cuyuna district. It had its first main level at 262 feet and its second at 362 feet. For many years the author, or his assistants, inspected this property during the progress of mining for one of the fee owners, and thereby secured much geological data. He also directed the drilling on some adjacent ground, and thus gained first hand knowledge of adjacent geology that is so valuable for correlating lithology rather than having to depend upon confusing recorded data of others.

The Kennedy mine has commonly been described and shown on maps as if it were on a single band of formation, spreading over these special and restricted parts of Secs. 29 and 30. The mining operations for the extraction of the ore were concentrated in five separate areas and these deposits were designated

by the operator by the names West, North, Midway, Intermediate and South, the names specifying their relative location to each other. In his earliest writings the author several times stated that the formation here consisted of a series of folds having a distinct N.E. pitch. Here, as elsewhere in the district, folding is responsible for the great widths of formation reported. Intricate folding is also responsible for the peculiar shapes of the ore deposits on different levels. Where the folding is locally simple, the orebody always had a simple outline. Where the outline was irregular, many twists and turns could be observed on nearly every level.

The band containing the North lens was the least affected by folding, and here the regular monoclinal succession of the beds shows a thickness of 300 to nearly 500 feet; whereas in the next band south, the crumpling, the folding, and the extent of erosion have left an exposure much greater than 500 feet in thickness. In the lower levels it could be seen that the bands of green schist first seen at the top were infolded, and some beds were walls below or above the original thickness of ore formation, and not interbedded lean or barren bands. For example, Harder and Johnston [38] said that the Kennedy belt was about 1,400 feet wide and included green chloritic schists. They considered these schists to be discontinuous lenses; they explained that many of the bands of hematitic schist (locally called paint rock) were altered green schists impregnated with iron, some being red at the surface and green in the lower levels. But these investigators had no opportunity to see how extensive and how folded the beds were in the lower levels.

In view of the northeast pitch and the feathering out of bands, some people have joined the most northerly and southerly bands eastwardly by a simple closed curve and pictured this as a single northeast-pitching anticline. This is particularly noticeable on commercial maps. Such connections may be correct for some minor bands, but there is certainly no justification for taking such liberties with the larger ones. Harder [39] was in doubt about

[38] *Op. cit.*, pp. 159 et seq.

[39] Harder, E. C., *op. cit.*, p. 461.

this structure, for he said that ". . . the Kennedy formation either died out or turned south and doubled back on itself; while south of the eastern end of it was the northeastern end of another iron-bearing belt." This latter belt is the broad one pictured as Bands IV. and V. in Secs. 31, 32 and 29, in Fig. 10. That anti-

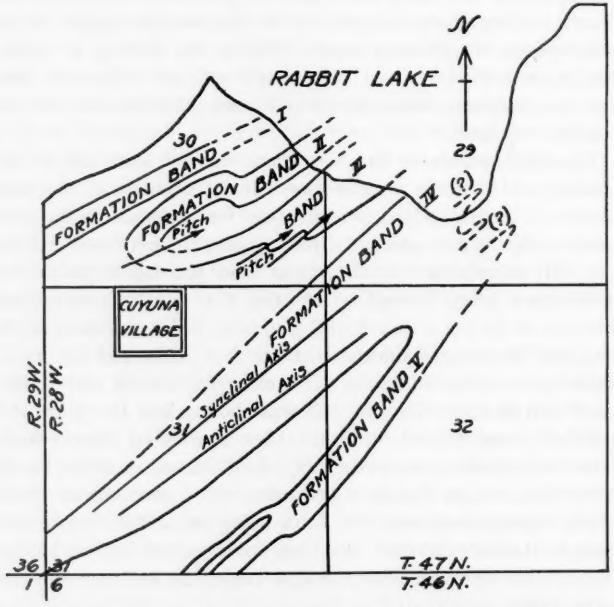

FIG. 10. Sketch map showing in plan the distribution of bands of ore formation in the vicinity of Cuyuna Village and the Kennedy Mine, T. 47 N.–R. 28 W.

clinal structures have been developed here, is true; but the anticlinal feature has a totally different significance than might ordinarily be supposed, so far as the bands of formation in both the Kennedy mine property and those areas lying immediately southeast are concerned. The principal or dominant structure is decidedly synclinal.

Fig. 10 is a sketch to show in plan the principal characteristics of the distribution of the several bands of ore formation in this area. Band No. I. dips south and is the eastward extension of the south limb of the anticline described for T. 47–R. 29 adjoining. Of this extension there can be no doubt. Again, 1¼ miles north, following the north shore of Rabbit Lake, in T. 47–R. 28, is the eastward extension of the north limb of the anticline, which measures about 6 miles in length. Drilling definitely links these extensions with the known bands in the areas westward. Bands II. and III. form an eastward-pitching syncline of short length. The north limb of this syncline is an undistorted southward dipping band, and in it, near the lake shore, is the North lens of ore; and in the small drag fold one quarter-mile west is the West lens, which has its longest dimension north and south. The south limb of this syncline is marked Band III. It contains a succession of folds and contortions that cause great width and irregular outlines in the Midway and Intermediate lenses, but less so for the South lens. Between Bands II. and III. is green schist. On the lower levels the minor folding is clearly evident and N.E.-pitches are frequently observed. The axes of the minor folds on Band III. extend into the wall rocks westward, and here one sees much infolding, with axes having sinuous courses.

Bands IV. and V. present much formation with only small pockets or streaks of ore, and none of the areas have been opened for mining. The dips in the drill cores and the variations in the rock layers and the structures in the mines to the west, suggest two synclines and an anticline, and there might be more. Band IV. is the more folded of the two, which is true also to the west, and, therefore, it is the wider one of these two. The N.E.-pitch presumably is also responsible for the poor exposure of the formation in the south half of Sec. 29, which accounts for the lack of desire to carry on more drilling here. To the southwest, on the continuations of Bands IV. and V., are the Portsmouth, Wearne, Evergreen, Croft and Meacham mines in T. 46–R. 29, all very important properties. Band V. is thin at the Croft, Meacham and other mines westward.

An idealized N.W.–S.E. cross-section for this area is shown in Fig. 11. Harder and Johnston [40] stated that, judging by the secondary structures in different parts of the Kennedy mine, the beds appeared to be on the south limb of an anticline. This is also the writer's opinion, but he believes that this anticline is the one so well indicated in T. 47–R. 29, which passes through Rabbit Lake, and of which Band I. in Fig. 10 marks the south limb.

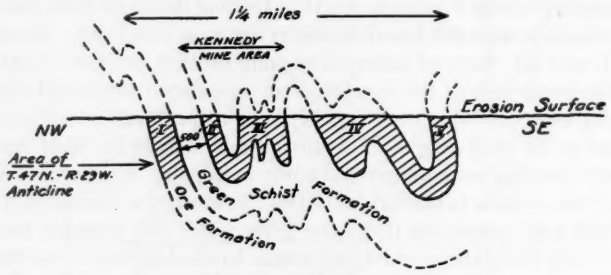

FIG. 11. Idealized cross section through Sections 29, 30, 31 and 32, T. 47 N.–R. 28 W. (Kennedy Mine area.)

Whether Harder and Johnston observed these secondary structures in only those parts of the Kennedy mine which by themselves are minor anticlines, cannot be told from their writings. However, the writer knows that Harder [41] was strongly of the opinion that the Kennedy formation taken as a whole was on the south limb of a large anticline that found its expression to the north, as is shown in Fig. 11. This was also the writer's view in 1916, the year when Harder and Johnston started their investigation.

Bands II. and III. are considered a part of the higher of the two layers of ore formation in the Cuyuna district, the formation so abundant in T. 46–R. 29. Here the upper Cuyuna band occurs as a subordinate infolded syncline which is separated from the remainder of the band. Band II., at the North orebody, has a layer of brown, high-phosphorus manganiferous ore at its base

[40] *Op. cit.*, p. 160.

[41] Harder, E. C., oral communication.

for a short distance, but drilling eastward in the lake-bed shows a greater length of it in that direction. Iron ores are the main product of concentration in this syncline, and they resemble those in T. 46–R. 29. The Intermediate lens, in Band III., had a large quantity of siliceous ore of the cherty and wash-ore types, as may be seen at the Maroco mine four miles westward, or the Rowe mine two miles south of the latter. It really seems that the synclinal structure between the Maroco mine and the property in Sec. 18 north of the Rowe mine in Tp. 47, R. 29 (see Fig. 9), and the one represented by Bands II. and III. at the Kennedy property in Tp. 47, R. 28, are corresponding linear elements of structure. This similarity may be only a coincidence, but it should be expected. The one drag fold, all that is yet known here, on Band II., and the serration on the south edge of Band III. are similar to what exists at the Maroco property and eastward (see Fig. 8). Certain features observed may also be the result of the same doming force. This dome can be observed to extend from the Maroco property on the west to these two bands at the Kennedy mine on the east. Whereas the doming produced S.W.-pitches in the Maroco and other adjoining deposits in Secs. 2 and 3 on the west, it produced, correspondingly, as would be expected, N.E.-pitches in the Kennedy folds on the east. These are exactly the features one would expect to find, and they should be given full consideration in these problems. In this area, the distance between the lower and upper major Cuyuna bands is about 500 feet, although it is not impossible that here a small band or lens may lie above the lower band and result in a smaller thickness, or separation, than that between the Maroco and Merritt mines six miles westward. Such overlying lenses occur elsewhere, as in Secs. 11 and 12, 46–29 (see Fig. 7).

SUMMARY.

Such observations as the writer has made have resulted in the accumulation of too much data to be discussed in full. The theory here presented is supported by a discussion of only a few critical unit areas. But these, incidentally, are the same ones

which have, at numerous times, been subjected to much speculation by others. The older theory that the North Range area is geologically older than the South Range, or that it is a single horizon, introduces many new difficulties and eliminates none of the old ones.

Unfortunately, in the Cuyuna district there are no natural rock exposures; those that become exposed by mining operations are almost immediately concealed, either by caving in mining, or by flooding of the workings. It is risky to make interpretations from drilling data only, because the terminology used and the classifications made by the engineer in charge of the drilling and shown on the exploration blueprints, are not what a geologist or a geological engineer would record. The reader must no doubt be impressed with the peculiar conditions under which geological information is obtained here, and that it takes many years of accumulation of data before plausible correlations and interpretations can be made over wide areas. Therefore, though much that has been presented here may appear clear to the writer, he is not able to produce certain evidence offered and discussed by him, for others to see, because it has been destroyed by mining. To some extent this deficiency may be met by the numerous writings by other investigators. It remains for observers to look for and find other facts, to be discovered principally in future operations, to show that the interpretations here offered are impossible or subject to much modification, perhaps by the writer himself. These points are stated to show that Cuyuna geologic structure is not speedily discerned or evolved, although it should not take another decade or two before a contribution limited to structural features is again made possible.

The hypothesis of structure described, seems to account for more features than any others tested by the writer, and may be briefly reviewed as follows. The whole area occupied by Cuyuna rocks is part of a huge synclinorium. The more restricted or ore-bearing portions of the Cuyuna district are on larger folds on the north limb, and these folds are themselves smaller anticlinoria and synclinoria, each of local significance and of limited extent. One important anticline occurs in the north part, or T. 47–R. 29;

another one in T. 46–R. 29, where it accounts for the Sagamore deposit; in all probability, as a large feature, one or more occur in the South Range. No one knows what there is between the last two anticlines named. The synclinal areas are between the anticlinal areas, but the most important one is that in the north part of T. 46–R. 29, where most of the producing mines are located. In places this synclinorium is a shallow basin and in other places deep; but numerous open folds and closely-pressed folds of local consequence have given a wide distribution to the ore formation in few places at the erosion surface. The north limb of this synclinorium is quite well defined, and it contains folds of considerable size down the dip of the beds, which have created a serrated edge around a dome-like elevation that has been eroded to a base-level, causing the absence of the ore formation in its expected place of occurrence. The doming has caused pitches in different directions corresponding with the slopes of its own sides, some pitches being opposite to the dominant pitch of the major structure. The ore formation occurs in at least two bands, one above the other and separated in one place by a thickness that may be 2,500 feet, of non-iron bearing rocks, but less if this area contains folds. This is a matter that has not yet been possible to determine. The synclinorium in T. 46–R. 29 is defined by the outcrop of the upper band of ore formation, and the whole synclinorium seems to rest mainly on the south limb of the anticlinorium which is exhibited by the outcrop of the lower band, best shown in Tp. 47, immediately to the north; while the south limb rests on a similar anticline, which, as now known, consists mostly of green wall-rocks but is indicated at one place by the ore formation containing the Sagamore deposit in Sec. 19, T. 46–R. 29.

The bands of ore-formation north of Tp. 47 are in all probability re-occurrences of these several bands as they rise to the erosion surface or dip down to meet it. Since the upper band shows thinning along its south edge, it may indicate the beginning of complete thinning out not far away from here, although for the present we can only assign its absence to erosion, or to inability to recognize its counterparts elsewhere.

A distinctive feature of both bands is that the lower horizon or basal portion is manganiferous; but the lower of the two major bands is proponderantly manganiferous, and the higher band is preponderantly non-manganiferous, except in a few restricted areas. In the higher band it may well be that the greater abundance of manganiferous material in some places is as much due to elevation by folding and the removal of the upper or non-manganiferous part by erosion, as to original differences in deposition.

If the South Range beds of formation do not constitute a third horizon but are the extension of an existing one northward, it seems more plausible at present to associate it with the lower of the two bands found on the North Range.

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THE TIME SEQUENCE OF HYPOGENE ORE MINERAL DEPOSITION.

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INTRODUCTION.

It has been known for many years that in ores of magmatic affiliation the minerals are deposited in a regular order, one after the other. If one looks over the published descriptions of ores where the mineral sequence is given, the similar arrangement in the many different districts is most striking. What does this mean? To put the question another way, what factor, or group of factors operate so as to produce in a large proportion of ore deposits a very common result? The answer lies at the heart of ore genesis.

An analogy might well be made with the succession of mineral deposition in ore deposits and in the Stassfurt Salt deposits, or with the order of crystallization of the minerals in igneous rocks. In each, the order of separation of the crystalline phase from the liquid is most intimately related to origin, and in the second case to the order of superposition of beds of different salts, in the last to the relations of different igneous rock masses as produced by differentiation.

In all three of these problems the ore, the salt beds, and the igneous rocks, there is a wealth of field data, but only in the latter two has any systematic effort been made to collect experimental data and use it to help explain that found in the field. The present paper is an attempt to collect and present some of the existing experimental data on the ore minerals as it is related to the common mineral sequence of ore deposits. It is essentially an arrangement of known data that have not been hitherto correlated. A tentative hypothesis is formulated to account for relations found, but it is realized that the data are too few for any definite conclusions. The hypothesis will at any rate serve as a reminder with regard to the main relations.

In a recent paper Lindgren [1] gives the time succession of minerals that is common to metalliferous veins. These minerals are listed in tabular form with some of their properties in Table II. With the exception of the anomalous group of minerals containing tin, molybdenum, tungsten, and bismuth a general progression of properties is apparent.

The succession of minerals as seen in polished sections of ores, as in thin sections of igneous rocks, is really the order of completion of crystallization. There can be no doubt that much overlapping of mineral deposition takes place, and it would doubtless be of theoretical as well as of practical interest if we could always determine by microscopic examination what percentage, if any, of overlap occurs. Unfortunately this is largely beyond our means at present.

A fact of much interest is that the sequence of introduction and deposition is also that of replacement.

Of much concern from the standpoint of this paper are the exceptions to the general rule in sequence. It is important first of all to notice that these exceptions are usually confined to one, two, or three minerals in a given deposit and these are usually not far from their appointed place. No occurrence is known where the sequence is completely reversed to that of the normal order in cases of deposits connected with igneous rocks. It is entirely possible that these variant sequences may, when carefully considered in connection with the geological setting, throw more light on ore genesis. A considerable number of sequences have been collected with this end in view, but they have not, as yet, been adequately enough studied so that the principal divergences from the general case can be given.

The minerals and their contained elements show some striking progressions in physical and chemical properties, which are tabulated in Tables I. and II., and which will now be discussed in some detail.

[1] W. Lindgren, "Magmas, Dikes and Veins," *Trans., Am. Inst. Min. Met. Eng.*, 74, p. 88, 1926.

TABLE I.

SUCCESSION OF ELEMENTS IN DEPOSITS OF MAGMATIC AFFILIATION.[1]

Base Metal.	Atomic No.		Acid Element.	Atomic No.	Melting Point.	Boiling Point.
Fe.....	26		O	8	− 218.4°	− 183°
Co, Ni....	27, 28		S	16	119.0°	444.6°
W.....	74	Anomalous Group	As	33	814 *	615
Sn.....	50		Sb	51	630.5°	1380.°
Mo.....	42					
Bi.....	83					
Zn.....	30	Note zonal vs. time relations				
Cu.....	29					
Pb.....	82					
Ag.....	47					
Au.....	79					

Some of the properties[2] discussed in this paper are tabulated opposite each element. A general progressive change is apparent. The elements are listed in order of first appearance in minerals. The first element to appear is at the top of the list; the others follow in order.

[1]See Table II., p. 13.

[2] The constants for the elements were obtained from the International Critical Tables and from Landolt Bornstein Physikalisch Chemische Tabellen, 1923.

PROGRESSION IN THE CHEMICAL AND PHYSICAL PROPERTIES IN THE SUCCESSION OF ELEMENTS.

The well-known table of Mendeljeff, which as constructed at present lists the elements in order of increasing atomic number, shows a periodic repetition of physical and chemical properties of the elements. It has proved to be one of the most powerful tools in modern chemical and physical research, because it expresses fundamental relationships between the elements. It is consequently of interest to know that the order of first appearance of the metals and also of the common non-metals (O, S, As, Sb), each being considered as a separate series, is in the approximate order of increasing atomic number or atomic weight.

In Table I. the common order of first introduction (or crystallization) of elements in veins is shown. The first element in the sequence is at the top and the later ones are in order underneath. The atomic number of each of these is given. Inspection shows

that tungsten, tin, molybdenum, and bismuth do not fit in the atomic number progression. As will be shown later, the physical and chemical properties of their compounds also do not fall into the mineral procession. In a later paper it will be shown that the deposits of these metals do not occur with the type of igneous rocks that their position in the mineral sequence suggests they should. In brief, this group of metals, minerals, and deposits appears anomalous with respect to the others. Since these various physical properties of the elements and minerals reflect their chemical properties, we may infer that some difference from the other ores in the chemistry of segregation or deposition is involved.

The sequence as given by Lindgren does not include titanium, vanadium, and cadmium, or mercury, in oxides or sulphides. The titaniferous magnetites which frequently contain vanadium and titanium would certainly be well up toward the first minerals, as would rutile, if they were added to Lindgren's list, and so it is of interest to note that their atomic numbers are low, that of titanium being 22, while that of vanadium is 23. Cadmium in the sulphide greenockite occurs later than sphalerite,[2] this position being proper in the series relative to the atomic numbers, that of zinc being 30, while cadmium is 48. Mercury with an atomic number of 80 would certainly as cinnabar be one of the latest minerals deposited if added to Lindgren's succession.

It is thus seen that although there are breaks and reversions in the progression of atomic numbers and atomic weights of the metals in the general mineral sequence of metalliferous veins, the strong trend toward higher numbers is certain.

Turning to the acidic radicles O, S, As, Sb, we find that the sequence is in complete order of atomic numbers.

Since there is a general progression upwards in atomic numbers of the elements in the vein sequence, it would be expected that there would also be a progression in other properties of these same elements. This is true, and some space will be devoted to several of these that are of most interest.

[2] W. Lindgren, "Mineral Deposits," 3d ed., 1928, p. 894.

Progression of Melting and Boiling Points and relative vapor Pressures of the succession of Acidic Elements.—The acid elements oxygen, sulphur, arsenic, and antimony, which appear in the order named, have progressively higher melting points. This is paralleled by a similar change in boiling point and hence probably also by progressively lower vapor pressures.

TABLE II.

	Schuermann's and Wells' Solubility Series of Sulphides Most Soluble at Top of Column.	Heat of Formation Gram Mol. Calories.	Hardness Mohs Scale.
Magnetite		265,200	6.0
Specularite			6.0
Pyrite			6.25
Arsenopyrite			5.75
Nickel cobalt arsenides			5.5
Wolframite	Anomalous group of minerals and elements		5.25
Cassiterite		137,800	6.5
Molybdenite			1.25
Bismuth			2.25
Bismuthinite		18,800	2.0
Pyrrhotite	Iron		4
Pentlandite	Nickel		3.75
Stannite			4.41
Sphalerite	Zinc	41,300	3.75
Enargite			3.00
Tennantite			3.5
Tetrahedrite			3.5
Chalcopyrite			3.75
Bornite			3.0
Galena	Lead	20,900	2.62
Chalcocite	Copper	19,000	2.75
Argentite	Silver	3,330	2.25
Ruby silver			2.5
Polybasite			2.5
Chalcopyrite			3.75
Electrum			2.75
Lead sulphantimonides	Mercury	235	2.5

A preliminary grouping of the statistical data on the igneous rocks associated with deposits of each of these minerals shows increasing siliceous character down through the table (excepting the anomalous group). Notable exceptions are silver, with diabase at Cobalt, Ontario, and heavy pyrite replacements connected with siliceous rocks, such as those in Shasta County, California.

Table II. shows general mineral succession by deposition or replacement in deposits of magmatic affiliation [3] with magnetite

[3] W. Lindgren, "Magmas, Dikes and Veins," *Am. Inst. Min. Met. Eng.*, No. 1575–I., p. 18, 1926.

deposited first and the lower ones later in the order given. This succession is matched (excepting bismuth sulphide) in the next column by Schuermann's and Wells' solubility series.[4] The minerals decrease in solubility down through the table. The heat of formation [5] and hardness [6] both show a general decrease down the column. Bismuth sulphide is anomalous in all these characters, its solubility, hardness and heat of formation all place it in the vicinity of galena and chalcocite.[6a] Cadmium sulphide follows zinc sulphide in the solubility series, as it also does in nature.[7]

PROGRESSION OF CHEMICAL AND PHYSICAL PROPERTIES IN THE SEQUENCE OF MINERALS.

Solubility Series.—The application of Schuermann's Series [8] to the hypogene sulphides appears to have been neglected by geologists. This series is one in which the sulphide of any metal will be precipitated at the expense of any sulphide above it in the table.

Under certain conditions any of these metals in solution will be precipitated as sulphide if in contact with the sulphide of a metal, above it in the table while the metal of the attacked sulphide will at the same time go into solution. In brief, the more insoluble sulphide, *i.e.*, the one with the greatest "affinity" for sulphur will form at the expense of the more soluble one.

Wells [9] by a study of fractional precipitation of sulphides in aqueous solutions obtained the same series, and states that the order represents the relative solubility of the sulphides in water.

It is, of course, impossible to apply Schuermann's series to the

[4] R. C. Wells, U. S. Geol. Survey, Bull. 609, p. 45, 1915.

[5] International Critical Tables. Landolt Bernstein, Physikalisch Chemische Tabellen, 1923.

[6] Dana's "Textbook of Mineralogy," 1922. Mean of data given.

[6a] Lindgren, oral communication. Later work shows that it occurs near this position.

[7] W. Lindgren, "Mineral Deposits," 3d ed., p. 982, 1928.

[8] For discussion of Schuermann's Series and Weigel's Solubility Series, see: R. C. Wells, "Electrical Activity in Ore Deposits," U. S. Geol. Survey, Bull. 548, p. 66, 1914; ——, "Fractional Precipitation of Ore-forming Compounds," *idem*, Bull. 609, p. 16. 1915; W. H. Emmons, "Enrichment of Ore Deposits," *idem*, Bull. 625, pp. 116–119, 1917.

[9] R. C. Wells, ECON. GEOL., vol. 5, p. 7, 1910.

sulphides with several elements since no data is available but the table lists the succession of simple sulphides given by Lindgren, along with Schuermann's Series. It can not be mere chance that has arrayed the simple sulphides in veins so closely parallel to the solubility series. This argument gains force when we remember that any one of the minerals in Lindgren's table typically replaces the one above it. It could not do this unless it were more insoluble at that time and place, than the one it replaces. For these reasons it is believed that the factor of solubility is at least of hypothesis value as one of the chief causes of hypogene mineral deposition. From the viewpoint of this hypothesis a dilemma is apparent. Why is the most soluble sulphide commonly deposited first?

The sequence as given by Lindgren is a replacement series in which any of the lower minerals in the table will replace any one above, but the important fact remains that it is also an introduction and depositional series which may and often does occur with little or no replacement.

Further discussion on these points will be given after more data is presented.

Heat of Formation.—There is a rough parallelism between Schuermann's Series and the electromotive series of metals, and it has been shown that Schuermann's Series parallels the mineral sequence in veins. Since the thermal effect of combination is connected with the position of the elements in the electromotive series, it might be expected that there would be a progressive change in the heat of formation of the different minerals in the vein sequence. This is found to be true.

The heat of formation has been determined for only a few minerals in the vein succession. Beginning with those minerals deposited first in the series, the heats of formation become successively less with the later minerals. Bismuth sulphide is again anomalous. This decrease in the heat of formation is probably connected with the lessening of the so-called " force of crystallization," or ability of the mineral to form euhedral crystals by replacement. There is, so far as the writer is aware, no known case of a mineral late in the series forming a euhedral crystal by re-

placement of the earlier sulphides. On the other hand, when a recurring generation of one of the early sulphides like pyrite or arsenopyrite forms along a replacement veinlet in the sulphides lower in the series, it may at times form euhedral crystals. Along the same lines may be mentioned the ability of the minerals early in the sequence to form euhedral crystals by replacement of granite, quartzite, slate, and in fact almost any kind of rock. In contrast it is known that those minerals late in the sequence like spalerite or galena typically form euhedral crystals only in the more easily replaceable rocks, such as limestone or dolomite.

Progressive Change in Hardness and in Metal Content.—It has been pointed out by Gilbert[10] that, beginning with the earlier minerals, there is a gradual decrease in hardness in the ordinary mineral succession.

Parallel to this change in hardness is a general increase in weight percentage of metal content down through the sequence, with a complementary decrease in amount of sulphur.

Other Processional Features.—It might be expected that since throughout the series there is a tendency toward increase in atomic weight of the elements there would be a corresponding increase in specific gravity. In the latter part of the series this is roughly true, but it must be remembered that specific gravity is a function of the atomic weights and also of the atomic volumes of the respective elements entering into the combination. There is a marked progressive increase[11] in atomic volume from oxygen through sulphur and arsenic to antimony, and a gradual decrease in atomic volume from Fe through Co, Ni, Zn to Cu, with Ag greatly increased over all. It is thus apparent that unless the effect of one of these factors greatly predominates a series will not result. Since there is a rough progression toward higher specific gravity in the latter part of the depositional series, we may conclude that here in general the factor of atomic weight is the most prominent.

[10] G. Gilbert, "The Relation of Hardness to the Sequence of the Ore Minerals," ECON. GEOL., 19, p. 668, 1924.

[11] W. L. Bragg, "Arrangement of Atoms in Crystals, *Philosophical Magazine*, 40, p. 178, 1920. The volumes are calculated from crystal data.

Another feature of interest is the relative complexity of molecules of the minerals in the series. In general the later minerals containing iron are more complex, *i.e.*, contain more elements, than the first ones. The reverse seems to be true of copper. Of interest is the fact that the native metals gold, silver, copper and lead, whether of hypogene or of supergene origin, are commonly later than their respective compounds.

DISCUSSION AND CONCLUSIONS.

The normal succession of minerals in veins as determined by Lindgren has been examined to see if any natural relations could be found.

The order of introduction of metals is approximately that of increasing weight, if we neglect the anomolous group, Sn, W, Bi, Mo, hence they form a progressive series in Mendeljeff's periodic table of the elements. The order of introduction of the acidic elements also is that of increasing weight. This order of introduction of metals also agrees roughly with the electrolytic potential series.

The melting points of the metals do not form a progressive series, but the acidic elements which are introduced in the order O, S, As, Sb, have progressively higher melting and boiling points from O to Sb. The vapor pressures of the acidic elements at a given temperature will probably decrease in the same order.

Those minerals which are deposited first have a higher heat of formation than the later ones.

The simple sulphides, excepting that of bismuth, are introduced in the order of Schuermann's Series. Wells[12] has shown that this series is one of solubility. The simple sulphides in hypogene veins are then normally deposited in the order of decreasing solubility. Since some of the physical properties, particularly that of hardness and metal content are gradational from one end of the series to the other, and since both hardness and the heat of formation are very likely a reflection of the chemical properties, it is possible that the whole series is one of solubility.

That solubility is important is suggested by the analogy of

[12] R. C. Wells, U. S. Geol. Survey, Bull. 609, pp. 16–17, 1915.

hypogene deposition and replacement with supergene enrichment. Supergene enrichment is essentially the formation of minerals lower in sulphur content and with a higher percentage of the heavier metals than the pre-existing hypogene minerals. Emmons summarizes the relation of solubility to supergene enrichment as follows:[13] ". . . the secondary replacements that are clearly of great economic significance are such as would be expected from the relations indicated by the Schuermann Series." The hypogene series shows the same feature of increase in weight percentage of metal content with lessening of the amount of sulphur down through the sequence. This argues for a similar cause, namely, solubility.

The question may well be asked, what is the meaning of these relationships? One thing seems clear that we are dealing, not with a mere fortuitous arrangement, but with a natural series. This is shown by the processional characters of solubility, hardness, percentage of metal and heat of formation.

With regard to the causes of mineral deposition Lindgren says:[14]

> The precipitation of a given metal in a complex solution is a problem dependent on no single factor: There are involved, temperature, pressure, solvent, concentration, relative abundance, reactions in the solution as precipitation progresses, character of country rock, and probably several other factors. Generally speaking it has been held that the metals present in abundance (like iron) would be precipitated first.

It would appear that some one or several causal factors trend in the same direction, and thus form a preponderant influence in one direction to produce this common series. When other factors become dominant a different order of deposition is found, such as hematite being later than chalcopyrite.

A fact that must be held in mind is that the natural sequence given by Lindgren is not alone a sequence of mineral replacement but also clearly the general order of introduction. This latter fact is clear, for the earlier crystals are often fractured with

[13] W. H. Emmons, "The Enrichment of Ore Deposits," U. S. Geol. Survey, Bull. 625, p. 140, 1917.

[14] W. Lindgren, "Mineral Deposits," 3d ed., p. 138, 1928.

introduction of the later minerals along the fracture planes. Some ore shoots in high temperature gold veins formed by late introduction of native gold along fractures are a large-scale example of similar facts commonly seen on a microscopic or hand specimen scale.

That forces the question back to the source of the metals in the vein solutions. It has been held that these are derived from the rocks traversed by the hot magmatic waters given off by igneous rocks or by the heated meteoric waters produced at the time of intrusion. Such an assumption is negatived by the fact that an examination of the literature on the ore deposits of North America brings out a strong association of different metals to different types of igneous rocks.[15]

This general correlation of each metal with a particular kind of igneous rock must indicate that the metals are largely derived from a magmatic source. If the metals are given off in solution from igneous rocks, at what stage or stages in the magmatic process are they given off? Why are they given off in sequence? Several possibilities present themselves. The minerals appear in the veins in the probable order of decrease of vapor pressure of their respective acidic elements. We might well imagine thus a release in pressure on a magma on intrusion which would permit gas bubbles to form. These would presumably form and stream upward in the order of decreasing vapor pressure, namely oxygen first, then S, As, Sb. They might conceivably carry droplets of immiscible sulphides, with them, as has been suggested. It is, however, difficult to picture the cause of the sequence of metals by such means.

The second possibility pictures the concentration as taking place at a later stage in the history of a batholithic intrusion, that is, after much of the magma had crystallized. In the late stages of crystallization the " rest magma " would become less basic and hence less capable of holding in solution the metals most soluble in basic rocks, *i.e.*, Fe, then Cu, etc. In brief, continuous crystallization of the magma would tend to make it continually more salic, and hence continuously lower its solubility for each of the

[15] The data bearing on this subject will be published at a later date.

oxides and sulphides in turn which would be given off in the ordinary vein sequence.

The last suggestion is that the magma at about the completion of crystallization has the more soluble sulphides picked up first by the water, and less soluble ones next, producing a continuous migration of minerals in solution in the order of their decrease in solubility. This would parallel a fall in temperature and probably also an increase in the amount of water.

With the data now available the best hypothesis appears to the writer to be some combination of the last two, with the first of these taking its larger part in the higher temperature deposits and the last coming more into play with those formed at lower temperatures. A continuously falling temperature is assumed. This then assigns to solubility an active role at the source, while the immediate cause of sequential precipitation is a parallel sequential concentration with falling temperature of the different metals dependent on differential solubility in the magma and in aqueous solution at the source.

All of these factors would trend to the same result and there may be others not now known.

With regard to veins and ores which show a marked divergence from the sequence given by Lindgren, it has been the writer's observation that when such occurs it is practically always accompanied by fracturing or shearing of the earlier minerals, with the anomalous mineral occurring in the new fracture, which strongly suggests that the normal change in composition of solution from a given magmatic source is usually about the same, while a marked break like hematite after chalcopyrite is the result of solutions from at least a slightly different portion of the source, that came in along a new sheared opening.

One of the chief points of interest is that we now have an explanation as to why there is a common replacement series among the sulphides. It is the order which would be expected from a consideration of Schuermann and Wells experimental work. On *a priori* grounds it would be expected that any sulphide being replaced by another must of necessity be more soluble

under the conditions obtaining during the process, or replacement would not take place.

It is perhaps fortunate that the replacement series is the same as the introduction series, for if one were inverted relative to the other we might expect to have ore deposits of much more disseminated character, since the earlier sulphides would not necessarily precipitate the later ones.

ACKNOWLEDGMENT.

Thanks are due to R. C. Wells, W. Lindgren, and M. J. Buerger, who kindly read and criticized the manuscript. They do not necessarily subscribe to the hypothesis presented.

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NEW OCCURRENCES OF GERMANIUM. I.[1]

JACOB PAPISH.

OCCURRENCE OF GERMANIUM.

GERMANIUM has been estimated to be present in the igneous rocks of the earth's crust to the extent of $x \times 10^{-10}$ per cent[2] and its lines were observed in the spectrum of the sun,[3] which substantiates its presence in the reversing layer of this star. The element was discovered by Winkler in 1886 as a constituent of a rare silver mineral found in Freiberg, Saxony, to which Weisbach[4] had given the name *argyrodite*. Two mineral specimens which had been found in Freiberg, one in 1817 and the other in 1821, were identified by Kolbeck[5] and by Frenzel,[6] respectively, as argyrodite. Penfield[7] described a specimen of this mineral from Bolivia, stating that the exact locality where it was found was unknown. To a stanniferous variety of argyrodite which was discovered in La Paz, Bolivia, Penfield[8] gave the name *canfieldite*. Prior and Spencer[9] described a similar mineral found in Aullagas, Bolivia, and Stelzner[10] proposed the name *frankeite* for a germaniferous sulphide mineral from Bolivia, the main metallic constituents of which are lead, tin and antimony. Khrushchov[11] also reported the presence of germanium in frankeite.

[1] This article forms one of a series, and is entitled by the author GERMANIUM, XXVI. The investigation upon which it is based was supported by a grant from the Heckscher Foundation for the Advancement of Research, established by August Heckscher at Cornell University.

[2] Clarke and Washington, *Proc. Nat. Acad. Sci.*, **8**, 114 (1922).

[3] Rowland, *Amer. Jour. Sci.*, **41**, 243 (1891).

[4] Weisbach, *Neues Jahrb. Min. u. Geol.*, **2**, 67 (1866).

[5] Kolbeck, *Zentralbt. f. Min. u. Geol.*, **1908**, 331.

[6] Frenzel, *Chem. Zentr.*, **1901**, I., 590.

[7] Penfield, *Amer. Jour. Sci.*, (3) **47**, 107 (1893).

[8] Penfield, *loc. cit.*, **47**, 451 (1894).

[9] Prior and Spencer, *Mineralog. Mag.*, **12**, 5 (1898).

[10] Stelzner, *Neues Jahrb. Mineral. Geol.*, **11**, 114 (1893).

[11] Khrushchov, *ibid.*, **11**, 119 (1893).

Krüss and Nilson [12] failed to get a test for germanium in fergusonite from Arendal, Norway, but Khrushchov [13] claimed to have found traces of this element in fergusonite as well as in tantalite, niobite and gadolinite. Khrushchov also stated that he recovered germanium from American samarskite, but this was disproved by Lincio [14] and by Dennis and Papish.[15]

Zinc blende from different localities was investigated by Urbain [16] who found that thirty-eight out of sixty-four ore specimens were germaniferous. The localities from which five of these ores originated were given by him as follows: Webb City, Missouri; Stolberg, near Aachen; European Turkey (in 1909); Raibl, Austria; and Mexico. Campo y Cerdan [17] noticed the presence of germanium in Spanish blendes and Hillebrand and Scherrer [18] in blende from Missouri and from Sunset, Idaho, as well as in *smithsonite* ore from Almont, Colorado, and from Nevada and Utah. Müller [19] reported germanium to be present in smithsonite from Livingston County, Kentucky and in the water from the same mine.

Hadding [20] observed that germanium was found in *cassiterite* from Finbo, Sweden, and from Mamaku, New Zealand, and Papish, Brewer and Holt [21] reported the presence of this element in specimens of cassiterite from the following localities: La Paz, Bolivia; Battle Mountain, Nevada; Ena Mino, Japan; Hot Springs, Alaska; Cornwall, England; Durango, Mexico; and Dawson, Yukon Territory.

The name *germanite* was given by Pufahl [22] to a sulphide mineral from Tsumeb, Southwest Africa, which contains copper,

12 Krüss and Nilson, *Ber.*, **20**, 1696 (1887).

13 Khrushchov, *Jour. Russ. Phys. Chem. Soc.*, **24**, 130 (1892).

14 Lincio, *Zentrb. f. Mineral.*, **1904**, 142.

15 Dennis and Papish, *Zeit. anorg. Chem.*, **120**, 21 (1921).

16 Urbain, *Compt. rend.*, **149**, 602 (1909).

17 Campo y Cerdan, *Anal. Fis. Quim.*, **12**, 80 (1914), *Jour. Chem. Soc., Abstracts*, 106, 270 (1914).

18 Hillebrand and Scherrer, *Jour. Ind. Eng. Chem.*, **8**, 225 (1916).

19 Müller, *ibid.*, **16**, 605 (1924).

20 Hadding, *Zeit. anorg. Chem.*, **123**, 171 (1922).

21 Papish, Brewer and Holt, *Jour. Amer. Chem. Soc.*, **49**, 3028 (1927).

22 Pufahl, *Metall. u. Erz*, **19**, 324 (1922).

germanium and arsenic as main constituents. Papish, Brewer and Holt [23] reported the presence of germanium in *enargite* from the following localities: Central City, Colorado; Ouray, Colorado; Butte, Montana; Braden Copper Company, Chili; Chiapas, Mexico; Tintic District, Utah; and Rising Star, Nevada. Germanium has been also found in certain mineral waters [24] and in the ashes of certain marine plants.[25]

The germanium content of the minerals mentioned varies all the way from negligibly small traces to appreciable amounts. Argyrodite and canfieldite, while rich in germanium, have not as yet been found in quantities large enough to be regarded important sources of this element. Germanite from Southwest Africa fulfills this demand to a considerable extent, and enargite from various localities, though much poorer in germanium, is of comparatively wide distribution and it may be regarded as suitable material from which to extract germanium. At one time Urbain [26] extracted germanium from Mexican sphalerite. This, however, is impractical because of the strikingly low yield: he obtained 4 grams of germanium from 550 kilograms of ore. In the extraction of zinc from American sphalerites the germanium is concentrated in a residue of zinc oxide, and until the recent discovery of germanite this residue has been the main source of germanium.[27] Flue dust and slags from copper smelters were investigated in this laboratory and some of them were found to be germaniferous. It is possible that these materials will become a valuable source of germanium, at least equalling the zinc oxide residues in importance.[28]

ARC SPECTROGRAPHIC DETECTION OF GERMANIUM.

Every chemical element when subjected to suitable excitation can be made to emit light, visible or invisible, and this light when

[23] *Loc. cit.*

[24] Bardet, *Compt. rend.*, **158**, 1278 (1914).

[25] Cornec, *ibid.*, **168**, 513 (1919).

[26] Urbain, *Compt. rend.*, **150**, 1758 (1910).

[27] See Buchanan, *Jour. Ind. Eng. Chem.*, **8** (1916); Dennis and Papish, *op. cit.*, p. 6.

[28] The results of the investigations will be published in a future article.

passed through an appropriate dispersing apparatus will be translated into a discontinuous spectrum characteristic of the excited element. The spectrum of an element covers an extremely wide range of frequency, and for the purpose of chemical identification the present discussion will be limited to the visible and the ordinary ultraviolet regions. These two regions when considered jointly are known as the optical range, which lies approximately between wavelengths 2100 and 8000 angstroms. By using what is known as the arc method of excitation the majority of the chemical elements can be made to yield spectra in this range. If the quantities of the elements used be small, the number of lines of a given spectrum will be few. It will also be noticed that very few lines of each element will persist even when extremely minute quantities of the element are present in the zone of excitation. These lines are spoken of as persistent and it is important that the analyst be familiar with them.

For reasons outside the scope of this article the grating spectrograph will be dismissed with the statement that it is inferior to the prism spectrograph for the examination of optical spectra from the standpoint of chemical analysis. Since the optical spectral range includes part of the ultraviolet, the optical train of the instrument is constructed of quartz, and photographic methods are resorted to during an analytical procedure.

A direct current arc of about 600 watts is satisfactory for exciting the substance to be examined. If this substance is a metal or an alloy in the form of rod, or wire, it can be used for the passage of the arc discharge. In the case of non-conductors of electricity such as minerals, natural and artificial, use is made of artificial graphite rods. These rods serve the double purpose of conducting the current and of holding the substance to be tested. They will also be found indispensable in connection with metals if the latter happen to be of such size and form that they cannot conveniently be made into rods or wires. In spectroscopic work the lower electrode is usually made the anode; it is much hotter than the cathode.

The range of photographic plates suited to the needs of the spectroscopist is quite wide. Ordinary commercial plates are

well adapted for work in the more refrangible visible region and in the ultraviolet. For shorter exposures the more rapid non-halation plates will yield good results. It should be borne in mind, however, that the spectral lines, which are the repeated image of the slit, are less harsh when obtained with slow plates. For the less refrangible spectral regions such as the green and the red, plates sensitive to these regions are procurable. The process of developing and fixing is similar to the one followed in ordinary photographic work [29] with the aim of obtaining very high contrasts.

When metallic germanium, or a compound such as the dioxide, is subjected to arc excitation, a number of spectral lines characteristic of this element will be observed. If solutions of a germanium compound of known but varied concentration be prepared and small, definite quantities of these arcked, an insight will be gained into the persistence of the spectral lines as conditioned by quantity of material in the zone of excitation.

The experimental work connected with this procedure was described elsewhere [30] and it will be quoted here for the sake of completeness, though in a somewhat modified form.

1.4408 gm. of pure germanium dioxide was introduced in water, solution being effected with aid of the least amount of potassium hydroxide, and the volume was made up to 100 cc., thus furnishing a solution containing an equivalent of one gram of germanium per 100 cc. From this stock solution, solutions containing 0.1, 0.01, 0.001, 0.0001 and 0.00001 gm. germanium per 100 cc. were prepared. The arc discharge was passed between the graphite electrodes for a few moments; it was then interrupted, to allow the electrodes to cool somewhat, and while the latter were still warm, a small, definite portion of each solution was placed on the lower electrode. These portions consisted of one-tenth cc. of solution and were delivered from a calibrated capillary pipette holding in all 0.12 cc. and divided into fiftieths of a cubic centimeter. Different electrodes and a separate plate

[29] For a discussion of the photography of the spectrum see Baly's "Spectroscopy," vol. 2, p. 357, Longmans, Green and Co., New York, 1927.

[30] See Papish, Brewer and Holt, *loc. cit.*

were used for each concentration, one spectrogram of the blank arc and four of the arc charged with the germanium material being obtained on a single plate. The charges actually placed on the lower electrodes contained 1, 0.1, 0.01, 0.001 and 0.0001 mg. of germanium respectively. The spectral lines observed at the different concentrations are given in Table I. In this table, as well as in those that follow, " v " signifies the fact that the line in question is visible, " f " that it is faint and " vf " that it is very faint. The investigation was limited to the spectral range between λ 4682 and λ 2198 angstroms.

TABLE I.

SPECTRAL LINES AT DIFFERENT CONCENTRATIONS.

	1 mg.	0.1 mg.	0.01 mg.	0.001 mg.	0.0001 mg.
4685.9.....	f				
4226.6[1].....	v	v	v	v	
3269.5.....	v	v	v	f	
3124.8.....	v	v			
3067.0.....	v	v			
3039.1.....	v	v	v	v	v
2829.1.....	v	f	f		
2793.9.....	v				
2754.6.....	v	v	v	v	
2740.4.....	v	v			
2709.6.....	v	v	v	v	
2691.3.....	v	v			
2651.6.....	v	v	v	v	f
2651.1.....	v	v	v	v	v
2644.2.....	v	v			
2592.5.....	v	v	v	v	
2589.2.....	v	f			
2556.3.....	v				
2533.2.....	v	v			
2498.0.....	v	v			
2436.4.....	v				
2417.4.....	v	v	v	f	
2397.9.....	f				
2394.1.....	f	f			
2359.2.....	v	v	f		
2338.6.....	f	f			
2327.9.....	f				
2314.2.....	v	f			
2198.7.....	v	f			

[1] Because of the low dispersion of a prism spectrograph in this range, λ 4226.6 of germanium is indistinguishable from λ 4226.7, a persistent line of calcium.

NEW OCCURRENCES OF GERMANIUM.

The spectrographic method just described was employed for the detection of germanium in a number of minerals. The mineral specimen or a portion of it was usually ground finely in an agate mortar and several small portions of the ground mass were removed at random and subjected to arc excitation. In the case of specimens that were obviously non-homogeneous, fragments from the various parts were examined separately. The amounts actually placed in the arc varied from five to ten milligrams.

Stannite.—Specimens from four different localities were examined and the results are recorded in Table II. Germanium was highest in the stannite from Cornwall, England and lowest in the sample from Santo Cristo Mine, Bolivia. Judging from the small number of lines and from their low intensity it is safe to conclude that only traces of germanium are present in stannite.

TABLE II.

GERMANIUM LINES IN SPECTROGRAMS OF STANNITE.

Stannite No.	Place of Origin.	2651.6.	2651.1.
1.	Itos Mine, Oruro, Bolivia	f	f
2.	Santo Cristo Mine, Oruro, Bolivia	v	v
3.	Zeekan, Tasmania	f	v
4.	Cornwall, England	v	v

Pyrargyrite.—Three specimens of Bolivian pyrargyrite were examined and the results are recorded in Table III. As seen from this table, Sample No. 2 contained a large quantity of germanium. Judging from the number of spectral lines and in the light of the experience with germaniferous materials gained in this laboratory, it is safe to assume that the germanium content of this specimen is upward of one per cent., possibly as high as three per cent. Sample No. 3, which insofar as could be ascertained came from the same mine, yielded upon arcking a smaller number of germanium lines, and its germanium content was estimated to be in the neighborhood of one tenth of a per cent. Since sufficient material was available, a weighed quantity of the

mineral was decomposed with nitric acid in a Pyrex distilling flask. The excess of acid was driven off by evaporation, hydrochloric acid was added and the whole subjected to distillation in a stream of chlorine. The purpose of the chlorine is to convert the arsenic to the pentavalent variety and thus prevent it from passing with the distillate. The germanium in the distillate was precipitated as the disulphide with hydrogen sulphide, removed by filtration and washed. It was next treated with ammonium hydroxide while still on the filter paper and oxidized to the dioxide with the aid of hydrogen peroxide. The liquid was removed by evaporation and the residue was ignited and weighed as GeO_2.[31] The results obtained were as follows:

Weight of pyrargyrite No. 3 taken	29.6 gm.
Weight of GeO_2 obtained	0.0317 gm.
Percentage of germanium	0.07

As seen from Table III. pyrargyrite No. 1 contains no germanium. The dealers from whom this specimen as well as the others were procured supplied the following information:[32]

The first specimen of pyrargyrite from Colquechaca, Bolivia, was obtained a number of years ago and we do not believe that it comes from the same locality as the second specimen which is labeled as coming from near Colquechaca, Dept. Potosi, Bolivia, as the latter lot we obtained from an entirely different source and at a much later date. The exact locality of the second specimen is Aullagas, near Colquechaca, Dept. Potosi, Bolivia.

In addition to the Bolivian pyrargyrite the spectrographic test for the presence of germanium was applied to specimens of pyrargyrite from the following localities: Granite Mountain Mine, Montana; Andreasberg, Harz, Germany; Coeur d'Alene District, Idaho; Austin, Nevada; and Guadalajara, Spain. In all of these germanium was found to be absent.

[31] For the detailed method of determining germanium see Johnson and Dennis, *Jour. Amer. Chem. Soc.*, **47**, 790 (1925).

[32] Private communication from Ward's Natural Science Establishment, Rochester, New York, dated November 22, 1927.

TABLE III.

GERMANIUM LINES IN SPECTROGRAMS OF PYRARGYRITE.

Pyrargyrite No.	3039.1.	2754.6.	2740.4.	2709.6.	2691.3.	2651.6.	2651.1.	2644.2.	2592.5.	2589.2.	2533.2.	2498.0.	Ge, estimated.
1.													None
2.	v	v	v	v	v	v	v	f	v	v	v	v	Large quantity
3.	v	v		v	vf	v	v	vf	v			v	Large trace

Pyrargyrite No. 1 from Colquechaca, Bolivia.
Pyrargyrite No. 2 from near Colquechaca, Dept. Potosi, Bolivia.
Pyrargyrite No. 3 from the same source as No. 2.

Native Copper.—Specimens of this mineral from seven different localities were examined.[33] It is seen from Table IV., which is a record of the examination, that traces of germanium were present in the copper. In addition to the spectrographic test, the copper from Globe, Arizona, was subjected to a chemical test similar to the one used in connection with pyrargyrite No. 3, and it was established that the germanium content of this specimen was very close to 0.001 per cent.

TABLE IV.

GERMANIUM LINES IN SPECTROGRAMS OF NATIVE COPPER.

Copper No.	Place of Origin.	2651.6.	2651.1.
1.	Butte, Montana	v	v
2.	Mednorudyansk, Ural, near Nizhne Tagilsk	f	vf
3.	Merrit, British Columbia	vf	
4.	Bisbee, Arizona	f	vf
5.	Globe, Arizona	v	v
6.	Somerville, New Jersey	v	v
7.	Lake Linden, Michigan	v	v

Calamine.—Fifteen specimens of calamine were examined for the presence of germanium and the results are recorded in Table V. The calamine from Wentworth, Missouri, (No. 15) was a brecciated variety intermixed with chalcedony and sphalerite.

[33] For the specimens of copper used in this investigation the writer is indebted to Professor Heinrich Ries, Head of the Department of Geology, Cornell University, and to Mr. C. H. Benedict of the Calumet and Hecla Consolidated Copper Company.

While this calamine gave no test for germanium, the sphalerite associated with it contained considerable traces of this element.

TABLE V.

GERMANIUM LINES IN SPECTROGRAMS OF CALAMINE.

Calamine No.	Place of Origin.	2651.6.	2651.1.
1.	Elkhorn, Mont.		
2.	Bleiberg, Carinthia	v	v
3.	Granby, Mo.	v	v
4.	La Duchessa, Sardinia	f	
5.	Friedensville, Penn.	v	v
6.	Malfidano, Sardinia	f	f
7.	Cumberland, England		
8.	Sardinia	f	vf
9.	Sanander, Spain		
10.	Joplin, Mo.	v	v
11.	Leadville, Colo.	f	
12.	Organ Mts., Dona Ana Co., New Mex.	f	
13.	Matlock, Derbyshire, England	f	f
14.	Ogdensburg, N. J.		
15.	Wentworth, Mo.		

Before postulating the origin of germanium in various minerals it is necessary to make a study of the state in which this element occurs in them. When one considers substances like enargite, sphalerite and pyrargyrite, the following questions suggest themselves: Is germanium present in these minerals in solid solution? Or does it retain its own mineralogical identity, being merely a member of a mixture?[34] Or does it occur isomorphously, displacing some other chemical element? There is no doubt that in attempting to settle these questions difficulties will be encountered in the case of those minerals which contain bare traces of germanium. There are however substances with an appreciable content of germanium, and it is hoped that through the efforts of the mineralogist knowledge will be gained of the mode of occurrence of this rare element.

SUMMARY.

This article contains:

An outline of the occurrences of germanium in natural min-

[34] Goldschmidt reported in 1908 that he found crystals of argyrodite on a specimen of pyrargyrite from Colquechaca, Bolivia. See *Zeit. Kryst. Min.*, **45**, 548 (1908).

erals as recorded in the geological and chemical literature from the time of the discovery of germanium to the present.

A description of an arc spectrographic method for the detection of germanium.

An announcement of the occurrence of germanium in stannite, in pyrargyrite, in native copper and in calamine, from different localities.

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ITHACA, N. Y.

THE ANCIENT MINING WORKS OF CASSANDRA, GREECE.

CORNELIO L. SAGUI.

If we follow the coast line of Greece from the Gulf of Orfano to Mount Athos, we still find the names of famous Greek cities that disappeared many centuries ago, but seem even now to fill with their impressive history that empty stretch of country gently bathed by the Aegean Sea. Names such as those of Amphipolis, Stagyre, Stratonikia, Acanthos, and others, still haunt that desert country like ghosts of the past. One is struck by such a vast desolation, and cannot recall that famous past without a sorrowful impression.

It seems incredible that nothing should remain of a civilization once so rich in industry and resources. However, one very important monument does remain of those days of yore, namely, the extensive underground works of an ancient mining and metallurgical industry.

It would be impossible to describe even briefly the numberless shafts and workings; the Lipzada mines, for example, near Stagyre (the birthplace of Aristotle), are like a labyrinth, with passages and exhausted stopes that extend for miles through the country rock. Coins of Alexander the Great and Philip the Third have been found by the writer in the deepest parts of these mines, and this suggests that the ore deposits were mined almost entirely before the time of Alexander the Great (356–323 B.C.). I have figured that approximately twenty-five centuries were necessary to accomplish such a vast amount of work.

Herodotus (484?–425 B.C.) seems to be the first historian who mentioned these mines, and he tells how under the reign of the Philips a horde of slaves toiled in order to mine the lodes of the Cassandra district and to extract the gold from a quartziferous gangue (πηρολητος). Krissites was the name of that mining

field, indicating its richness, but the ancient writers seem to ignore its history before Philip III, and even Diodorus indicates the reign of the Philips as the time when it was discovered by Crenidos. We may be grateful to Crenidos as the very pioneer of prospectors, and even to Diodorus, who tells the story, but the facts point so strongly in an altogether different direction that even with the utmost respect to the Greek scholars, we must stick to them.

The only possible way to reconcile these facts with Diodorus' historical opinion would be to suppose that Crenidos inspected the mining field of Krissites after a period of forced inactivity, due probably to wars, which, though not so dreadful as those of our more civilized times, were still destructive enough to stop altogether, even for centuries, an important industry.

This is so unfortunately true that if we refer to a capital example such as that of the Roman domination, we are immediately convinced how simple it was to reduce a flourishing country to a mournful land of drudgery and misery. When Paul Emilius, a celebrated Roman general, no doubt, conquered Thessalonica, the Krissites mines seem to have discontinued their activity for at least ten centuries—which seems an exaggerated toll to be paid even to a famous warrior. If history would teach something!

After Paul Emilius' conquest a long silence prevailed over the once flourishing mining field, and only towards the end of the Middle Ages does a new period of work seem to have dawned upon the Cassandra district. However, very little is known of this period.

According to the report of a French traveler, who visited the district in 1554, about six hundred furnaces were active along the valley on the north side of Mount Athos, which extends for about ten miles from Piavitza to Stratony, near the sea. These furnaces, it is reported, were used for gold extraction, and were situated along the streams so as to utilize the water power required to operate them. Siderokapsa ("burnt iron") was the most important town of the district. Some huge, dark ruins of towers still stand as a reminder of those prosperous times, near

Makala, a small village which has taken the place of Siderokapsa. Mining continued up to about the year 1600, and then practically ceased until modern times.

Geology.—At this point a geological sketch of the country is necessary. A main vein, sixty feet thick, known for a length of about ten miles, strikes east-west and dips about 50° south (see Fig. 1). The hanging wall is composed of azoic schists and the footwall of eruptive rocks (some pegmatite), which have deter-

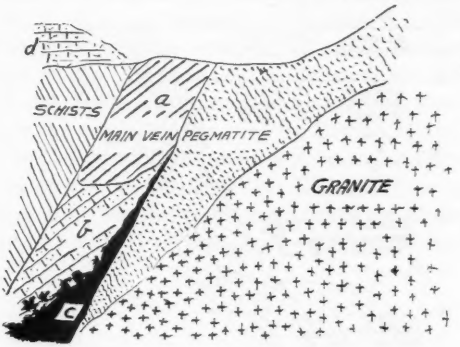

FIG. 1. Sketch of vertical section at Piavitza. *a*, manganese minerals; *b*, calcite with some pyrite; *c*, sulphides; *d*, limestone.

mined the general features of the area. A great number of veins striking north-south and crossing the main vein represent a more recent period of formation. Other veins strike parallel to the main vein.

The deposits contain gold, silver, lead, zinc, and a little copper. The minerals include pyrite, galena, zincblende, mispickel, lollingite, quartz, rhodochrosite, rhodonite, calcite, and oxidation products of iron and manganese minerals.

The upper oxidized part of the deposit was mined years ago for manganese (pyrolusite), of which the content was 40 to 55 per cent. The pyrolusite ceased at a depth of about 45 feet below the surface, where it gave way to rhodochrosite and rhodonite

(see Fig. 2). This part also has been mined for manganese at Piavitza down to about 400 feet. At a depth of about 600 feet manganese carbonate gave way to calcite, quartz, and the metallic minerals. A zonal arrangement is evidently present (see Fig. 1).

The gold and silver content increased with increasing pyrite and galena. In the Ferdinando shaft, with 10 per cent. lead, the gold ranged from 6 to 10 dwts. per ton, and 16 per cent. lead carried 0.5 per cent. of silver.

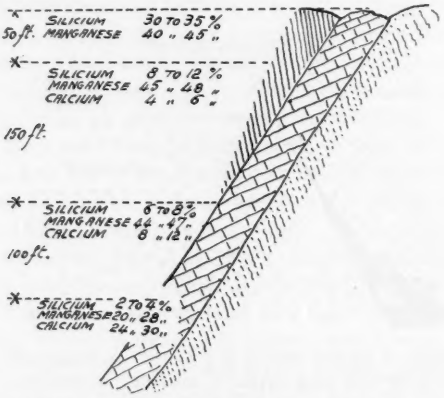
SILICIUM 30 TO 35 %
50 ft. MANGANESE 40 „ 45 „
SILICIUM 8 TO 12 %
MANGANESE 45 „ 48 „
CALCIUM 4 „ 6 „
150 ft.
SILICIUM 6 TO 8 %
MANGANESE 44 „ 47 „
CALCIUM 8 „ 12 „
100 ft.
SILICIUM 2 TO 4 %
MANGANESE 20 „ 28 „
CALCIUM 24 „ 30 „

FIG. 2. Vertical sketch at Piavitza, showing changes of silica, manganese and calcium with depth.

The ancient miners worked principally the lodes situated at the crossing of the two series of veins, where far the richest ores were found, carrying an average of over 15 dwts. of gold per ton and sometimes about one per cent. of silver. Marcasite and pyrite were the prevalent minerals, with some galena, but the richness in gold and silver above noted was certainly not frequent.

Workings.—As a rule the ancient shafts were dug at the crossing of two veins, and the lode was followed downwards by a long series of somewhat irregular stopes, the country rock being left untouched where it was possible. Empirical criteria of economic

geology seem to have been known to these ancient workers, since they followed as a rule the crossing points of the veins even where these were barren. I have also observed underground crosscuts directed to the crossing of two veins.

These miners certainly had a topographic method in planning the details of the underground workings, since it would be impossible otherwise to understand why they made passages between two distant points and through barren rocks.

Their method of tunneling was also extremely interesting. They traced by chisel and hammer a cut about five inches deep and one inch wide along the profile of the tunnel front, and thus were able to cut the remaining rock easily, since one side of the cut was always free. The same method has been observed by the writer in the ancient workings of the Bottino Mines.[1]

Passageways are frequently found so narrow that one wonders how miners of average size could get through. The slaves of those days probably adapted themselves to such conditions. Miners, at least under the Greek rule, lived underground, and once a

FIG. 3. Sketch of miner's lamp.

week came out to breathe the free air and to behold the skies. Their subterranean abodes are still visible; large abandoned stopes were utilized as kitchens and sleeping chambers, where traces remain of fire places, and holes still open in the country rock were used as cupboards or lamp niches (Fig. 3). Rough drawings are sometimes found, among which large suns are frequent, as if those laborers had desired to recall to their imprisoned bodies that the soul at least was always free and might, after all, remember that the real sun was shining somewhere. Very interesting are those underground villages, but the living

[1] C. L. Sagui, "Primary and Secondary Ores of the Bottino Mines, Italy," ECON. GEOL., vol. 19, No. 6, 1924. C. L. Sagui, *Mem. Soc. Lunigianese*, G. Capellini, vol. 2, No. 4, 1921.

vision of that horrible toil seems still to pervade the dark and voiceless workings.

The ores were lifted by small skips hauled out by a rope, sometimes guided by a wheel placed on the brim of the shaft, but more frequently rubbing against the rock, where deep-graved flutings still bear witness to that painful toil.

Underground waters undoubtedly limited mining under a certain depth, and a tunnel more than a mile long to clear the workings of water is still in existence near Mademilako. A mountain is tunneled through for this great distance by following a sinuous line to avoid the harder rocks. The dimensions of the tunnel are extremely small, about 20 inches wide and 32 inches high, only a bit wider near the floor. Some timbering was employed, in frames of three timbers.

Smelting Practice.—No information is available as to the ancient practice in gold and silver smelting, but I am inclined to believe that it was not much different from that described by the French traveler mentioned above, from whom I quote almost entirely on this point. I am helped in such reconstruction, however, by the study of furnace ruins that I have found buried under the old slags.

The ore, after roasting in the open air, was charged in small furnaces connected with a crucible where smelting took place. The entire plant was strongly built, and only the front of the furnace was closed by a light wall, which was demolished every Friday night when work was stopped. On Monday operation was again started by discharging the cooled furnace and recharging with layers of ore and charcoal.

The blowing engines were a series of straight tuyéres inclined toward the bottom of the crucible, through which the airblast was forced by bellows operated by a water wheel appliance. These wheels carried eight arms, four of which were used to operate the bellows, while the other four operated the cupellation plant in the same manner. The entire plant comprised two buildings, one on each side of the stream. Fig. 4 shows the blowing engine as I have endeavored to reconstruct it.

The furnace was charged through an ample mouth, underneath which were two holes, one near the bottom, through which the

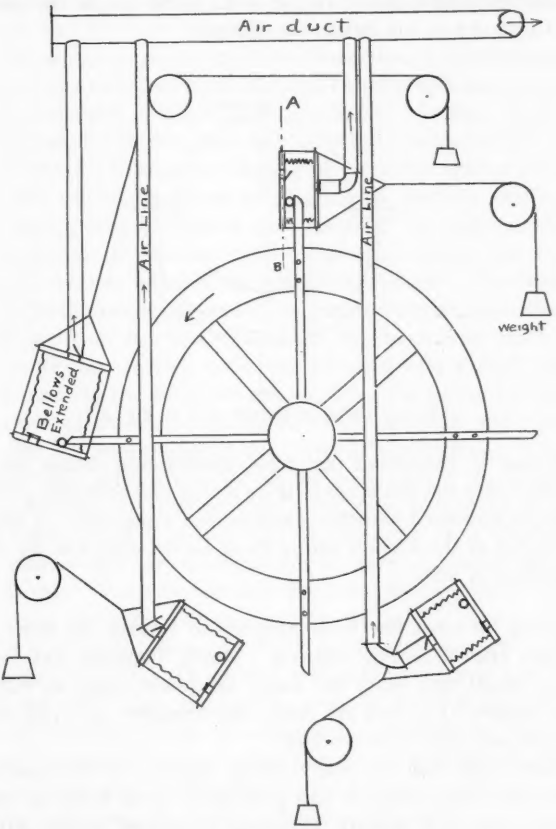

FIG. 4. Sketch of blowing engine.

molten lead was discharged, and the other about at the center, for smoke discharge. Cupellation furnaces seem to have been heated by firewood, and horizontal tuyéres were used.

It was the rule not to mix flux with mineral; this practice was a serious hindrance to regular work, and tuyéres were easily closed up, until a chance visitor to the mines taught the smelters of Cassandra to add flux to the charge.

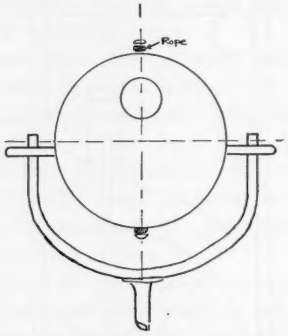

FIG. 5. Detail of section *A–B* in Fig. 4.

It may be considered that these metallurgical details are out of place here, but this is not so if we realize that economic geology with its associated branches, smelting and topography, is one of the oldest of the sciences and in those far-off days was the most important of them.

Along the coast line from Stratony to Kavala, are other important ancient mining districts. Mount Pangeon was intensively mined, and many old shafts are found along its valleys. The country rocks here are gneiss and limestone, and rich veins of gold and silver were worked.

Labor was then extremely cheap; metals, on the contrary, were very dear; hence it was possible to work lodes of much smaller size than modern industrial conditions would permit. The ancient miners were remarkably accurate in preparing the ores for smelting, since they knew well that an error made in the mine is always paid at the smelter. They were obliged, also, to depend upon their smelter returns instead of upon assays to determine their ore valuations.

In the old workings at Piavitza I once found a small ore deposit, and thus had the opportunity to note the criteria followed by those ancient workers in selecting their smelting material; the quality and size were carefully considered.

The economic geology of those times, though entirely empirical, was certainly well developed, and extreme skill and care were used in studying local geological conditions. In fact, where the ancient miners worked they left nothing of value behind them. It is doubtful whether economic geology in our present sense of the term can be considered to have existed, but it is certain that the same geological criteria were followed; the richness of ore at points of intersection in the veins was realized, apparently also the tectonic origin of the mineralized fissures. For example, at the Bottino mines I noted a crosscut of Etrurian time, directed from the main vein to a parallel one; this latter, a barren fissure not more than an inch wide, was followed with a small tunnel. Not far away the work was stopped, since the fissure had almost disappeared, the miners having evidently concluded, and correctly so, that this fissure was not one of the mineralized type which at the Bottino mine are linked to the main vein. The numerous complications of faulting were sufficiently understood to trace the continuation of a lode over an important fault, whereas in the past century our modern geologists have not always been able to do this. We must conclude that some favoring deity, presiding over the science of geology, guided them in their research.

In working the mines, no details were overlooked which might facilitate the task. The miners preferred working in hard rock, and the attack upon this was so methodical and skilful that the smaller fissures or vugs were thoroughly utilized. Lodes in soft rocks were not mined, as a rule, since it was difficult and dangerous to keep the workings open. In Sardinia, for instance, the ancient workings are found in limestone but not in schist, as the latter is there a soft rock.

A gap of many centuries intervenes, as I have said, between the Paul Emilius conquest and the second mining period of Cassandra, but along the Piavitza valley it is almost certain that a

small mining industry continued through the dark centuries. Slaves were probably not employed after the fourth century, since the Christian doctrine had spread a milder spirit over the world, but the mining profession was presumably kept alive as were other trades in those days, by guilds, the secrets of whose methods were handed down through the generations. The Comacine masters, for example, the remarkable mason guilds which built almost all the cathedrals of Europe, kept hidden throughout the Middle Ages the precepts of the *de Architectura* of Vitruvius.

In the ninth century, when the monks of Mount Athos founded their still famous convents, the mining industry in the Cassandra district probably passed into their control. In the second period of Byzantine architecture, extending from the eleventh to the fifteenth century, the Cassandra mines, like other mining districts of the Near East, undoubtedly reflected the splendor of the brilliant Byzantine Empire of that period.

From these brief notes it may be seen that an archeological history of economic geology would be of interest, since so many monuments still remain of this ancient science; we may even say that the most imposing monuments of the pre-Hellenic period are to be found in the historic mining districts of the Mediterranean shores.

In conclusion, I desire to express my warm appreciation for the suggestion and help given me by Professor Alan M. Bateman.

CORBEIL, PARIS,
FRANCE.

EDITORIAL

THE SEDUCTIVE INFLUENCE OF THE CLOSED CONTOUR.

THE theory of structural control of oil and gas occurrence was first successfully brought forward by the late I. C. White. The use of contours for expressing structure was introduced by W. T. Griswold.

In the early history of petroleum geology, information as to structure was almost the sole contribution of the geologist toward prospecting for oil. It is still his chief contribution. Structure was first expressed on maps by the use of cross sections and dip and strike symbols. With the development of greater refinement in mapping structure, and particularly in mapping the gentle type of Mid-Continent structures, and with the development of sub-surface geology, contours came to be used almost solely to express structure. The result, after a dozen years, is that the oil prospector—rich man, poor man, beggar man, thief—has learned to read and appreciate the geologists' structural contour map.

He may appreciate it more than it deserves. The desideratum in the popular mind, is the dome or closed anticline, best expressed by concentric contours—the closed contours. If the evidence is weak or lacking, the geologist may salve his conscience by using dashed or dotted contours, but if his map is well drawn, even though it expresses but a pious hope, the prospect is generally regarded as a good one if it "shows closure." The very terms "closed" and "closure" have come to be used as descriptive of structure from the terminology of contouring.

It was bad enough while the supply of closed structures was great enough to meet the demand. Petroleum geology has gone far afield, however, as the extension of aerial geologic surveys has restricted the possibilities of finding more structures and is endeavoring to extend its usefulness in areas where the surface

rocks do not express sub-surface structure. The geophysical methods have come in, and we are now trying to unravel structural complexities by a consideration of gravity anomalies, variations in the earth's magnetic field, identification of rocks by their elastic properties as revealed by different velocities of sound wave transmission, thermal gradients, or differences in electrical resistances. This is as it should be, and speaks well for the resourcefulness and competence of the geologist as a prospector.

That irregular curved line—descendant of the topographic contour—however, is an extremely useful instrument for the graphic expression of almost any type of variation on a plane datum. We are now working with iso-magnetic lines, iso-therms, isogams to express gravity variations. The resulting map may be clear to the geologist and even more clear to the physicist, but to the executive and layman, accustomed to structure-contour maps, the irregular concentric rings marking variations in intensity of various effects are recognized as of slightly different vintage but regarded, in lieu of interpretation, as much the same thing. One must admit, as an oil geologist with more than average acquaintanceship with geophysical methods, a very real quality of attractiveness in maps of this sort, even though there is an uneasy mistrust, born of bitter experience, as to the validity of such attraction.

The layman, regarding technical matters as too much of a mystery to admit of easy comprehension, has learned to think in contours rather than what they symbolize, and the result, with the introduction of geophysical methods, and expression of physical data in iso-lines, is likely to result in disappointments greater than ordinary.

This is a part of the great problem—the problem of geophysics and the problem of all prospecting and geology—the problem of interpretation. The solution is not in sight but it behooves the geologist to work earnestly and sympathetically with the physicist to the end that their results may be translated, as exactly as possible into structure maps—into the language that the oil producer and executive have already learned to read.

E. L. De Golyer.

DISCUSSION
AND
INFORMAL COMMUNICATIONS

THE ORIGIN OF ARTESIAN PRESSURE.[1]

Sir: In a recent number of ECONOMIC GEOLOGY, Russell [2] has argued against regional movement of the ground water in the sandstone beds which lie immediately beneath the Granerous shale in the Dakota artesian basin and has postulated that those sandstones contain only connate water to which no accessions have been or are being made from rainfall. His paper is a wholesome reaction against the conventional concept of the qualifying factors of the artesian condition in the Dakota basin, a concept which has long been dogmatically accepted even though some of these basic factors have never been tested by adequate quantitative data. The paper is, therefore, a stimulating challenge which goes far in delineating the problems of the Dakota artesian basin. However the corollary of Russell's hypothesis—that ultimate depletion of the artesian supply is inevitable—is of vast economic import, so that it seems wise to point out some respects in which the evidence presented is not necessarily conclusive in disproving a regional movement of the ground water in response to differences in hydrostatic pressure and in disproving an annual increment to the supply from rainfall.

STRATIGRAPHY AND LITHOLOGY.

The problem of the Dakota artesian basin involves the stratigraphy of the Cretaceous beds below the Greenhorn limestone, a

[1] Published by permission of the Director, United States Geological Survey. The writer wishes to acknowledge his indebtedness to colleagues of the United States Geological Survey for constructive criticism and discussion of the paper.

[2] Russell, W. L., "The Origin of Artesian Pressure," ECON. GEOL., vol. 23, pp. 132–157, March–April, 1928.

regional index stratum. As is shown by the accompanying sketch (Fig. 1), the conventional section at the western edge of the basin in the vicinity of the Black Hills, embraces the Lakota sandstone, Minnewaste limestone, and Fuson shale of the Lower Cretaceous overlain successively by the Dakota sandstone (Fall River

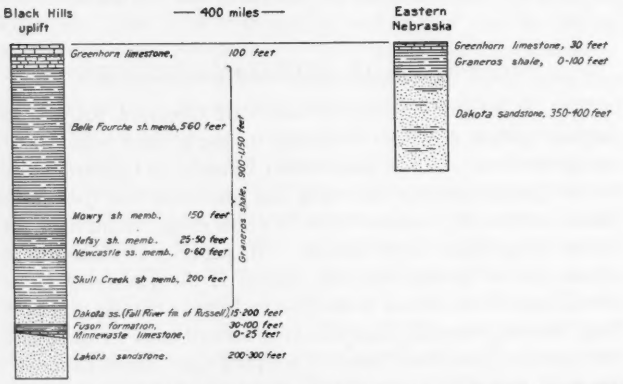
Black Hills uplift
400 miles
Eastern Nebraska
Greenhorn limestone, 100 feet
Belle Fourche sh. memb., 560 feet
Graneros shale, 900-1150 feet
Mowry sh. memb., 150 feet
Nefsy sh. memb., 25-50 feet
Newcastle ss. memb., 0-60 feet
Skull Creek sh. memb., 200 feet
Dakota ss. (Fall River fm. of Russell), 15-200 feet
Fuson formation, 30-100 feet
Minnewaste limestone, 0-25 feet
Lakota sandstone, 200-300 feet
Greenhorn limestone, 30 feet
Graneros shale, 0-100 feet
Dakota sandstone, 350-400 feet

FIG. 1. Comparative sections of some Upper and Lower Cretaceous strata in the Dakota basin.

formation of Russell), the Graneros shale, and the Greenhorn limestone. The Dakota sandstone ranges in thickness from 15 to 200 feet, the maximum occurring in the southeastern part of the uplift and the minimum in the northern part.[3] The Graneros shale, which is 900 to 1,150 feet[4] thick, is subdivided locally into five members—the Skull Creek shale, 200 feet thick; the Newcastle sandstone, 40 to 60 feet thick; the Nefsy shale, 25 to 50 feet thick; the siliceous Mowry shale, 150 feet thick; and the Belle Fourche shale, 560 feet thick.[5] Rubey[6] points out, however,

[3] Darton, N. H., "Artesian Waters in the Vicinity of the Black Hills, South Dakota," U. S. Geological Survey Water-supply Paper 428, pp. 19 and 27, 1918.

[4] Darton, N. H., and Paige, "Sidney," U. S. Geol. Survey Geol. Atlas, Central Black Hills folio (No. 219), 1925.

[5] Collier, A. J., "The Osage Oil Field, Weston County, Wyoming," U. S. Geol. Survey Bull. 736, pp. 79–84, 1923.

[6] Rubey, W. W., oral communication.

that the thickness and lithology of these members vary greatly within the region, and that the Mowry shale, for example, has not been recognized as such in the southeastern part of the Black Hills uplift. The section on the eastern edge of the basin includes the typical Dakota sandstone, 350 to 400 feet thick; the undivided Graneros shale, which is 105 feet thick in northwestern Iowa[7] and is thin or absent at least locally in eastern Nebraska;[8] and the Greenhorn limestone, about 30 feet thick. At the type locality in northeastern Nebraska—the bluffs of the Missouri River about 5 miles south of Sioux City, Iowa—only the uppermost 50 feet of the Dakota sandstone is exposed. The first fossils collected from this locality were marine and brackish water invertebrates which probably came from the uppermost sandstone stratum. Elsewhere along the eastern side of the basin, however, plant-bearing beds are exposed at several horizons in the Dakota, the lowest being about 200 feet below the top of the formation.[9]

Russell's[10] collection of fossil plants, reported to have come from the Newcastle sandstone member of the Black Hills section, has been found by Berry to correspond to the pre-Dakota flora of the Cheyenne sandstone of southern Kansas. From this is inferred the corollary that the typical Dakota is younger than the Dakota of the Black Hills section (Fall River formation of Russell). Furthermore, it is suggested that this corollary is substantiated by the flora of the Dakota of the Black Hills and by the eastward convergence of the Greenhorn limestone and the sandstones which are subjacent to the Graneros shale. Russell's line of thought leads to the inference that such a difference in age between the Dakota of the Black Hills and the typical Dakota of

[7] Todd, J. E., U. S. Geological Survey Geol. Atlas, Elk point folio (No.156), 1908.

[8] Burchard, E., "Geology of Dakota County, Nebraska, with a Special Reference to the Lignite Deposits," *Acad. Sci. and Letters of Sioux City, Proc.*, 1903–4, vol. 1, pp. 149–150, 1904. Condra, G. E., "Geology and Water Resources of a Portion of the Missouri River Valley in Northeastern Nebraska," U. S. Geol. Survey Water-supply Paper 215, p. 11, 1908.

[9] Stanton, T. W., "Some Problems Connected with the Dakota Sandstone," *Geol. Soc. Amer. Bull.* 33, pp. 255–256, 1922.

[10] Russell, W. L., *op. cit.*, pp. 134–136.

Nebraska establishes a total discontinuity of permeable beds across the basin. Three lines of reasoning, however, combat such an inference.

First, the Newcastle flora seems to contain at least two facies, of which one corresponds to the Cheyenne and the other to the typical Dakota. The Dakota facies has been established by Knowlton's assignment of Stanton's [11] collection from the vicinity of Hermosa, South Dakota, and two collections by Rubey [12] from the same general region. Stanton's collection has also been reexamined and its assignment to the Dakota affirmed by Berry.[13] The consequent dilemma in the precise correlation of the Newcastle member is typical of the stratigraphic problems of the Dakota basin. To sum up the available data, it seems extremely doubtful if the conclusion is justified that the Dakota sandstone of the Black Hills is necessarily older than all parts of the typical Dakota sandstone of Nebraska. Russell's assignment of the beds represents one extreme of the possible interpretations; the opposite extreme is that they are at least in part contemporaneous.

Second, studies by Rubey [14] and Stanton [15] indicate that the beds subjacent to the Graneros shale in the Dakota basin are river channel, river flood-plain, tidal swamp, beach, and shallow marine sediments transported by westward-flowing streams and deposited along and adjacent to a strand line which migrated progressively northward and eastward. The marine advance was intermittent, with possible minor reversals, so that in a given section the sediments ranged from fine to coarse and from continental, through brackish water, to marine. If, however, coarse materials were deposited at some places along this strand line throughout the period of transgression, as seems not unlikely, there must have resulted a zone which was continuously permeable even though it may have been circuitous and though successive

[11] Stanton, T. W., *op. cit.*

[12] Rubey, W. W., oral communication.

[13] Berry, E. W., "The Cretaceous Floras of the Black Hills."

[14] Rubey, W. W., and Bass, N. W., "The Geology of Russell County, Kansas," Kansas State Geol. Surv. Bull. 10, Pt. 1, pp. 54–65, 1925.

[15] Stanton, T. W., *op. cit.*, pp. 263 and 270.

sections may not have been contemporaneous in the minor units of the geologic time scale. That the Dakota beds (including Russell's Fall River formation) actually constitute such a zone is the most apparent interpretation of the records of the many wells which have been drilled in the basin.

Third, in such current-bedded rocks as the typical Dakota beds of the eastern side of the basin, it is likely that many of the masses of sandstone which in the plane section of an exposure appear to be detached lenses are in fact inter-connected parts of a pipe or tongue of coarse permeable sediment which is somewhat tortuous in horizontal plan. Furthermore, materials such as the siltstone that encloses the sandstone lentils of the typical Dakota, although usually termed impermeable, restrain but do not necessarily prevent the transmission of water under an adequate hydraulic gradient. From such information as is at hand, it does not appear that the lenticular character of the Lakota and overlying sandstones of the Black Hills, and of the Dakota beds of the east side of the basin, is necessarily an adequate barrier to movement of the low order of magnitude postulated by Meinzer and Hard.[16]

Neither the age relations established by the fossil plants, the mode of deposition of the sandstone beds, nor the detailed lithology of the beds, constitutes a valid demonstration that the permeable zones of the Lakota and overlying sandstones are discontinuous with those of the typical Dakota sandstone or that regional movement of ground waters is impossible. Indeed, full consideration of these factors suggests that the existence of continuously permeable zones is the more probable condition.

STRUCTURE.

The primary structural feature of the Dakota artesian basin is a somewhat irregular, open, canoe-shaped trough whose axis trends about N. 30°W. through north-central Kansas, Nebraska, and western South Dakota, and then swerves toward the west as it crosses North Dakota and extreme northeastern Montana

[16] Meinzer, O. E., and Hard, H. A., "The Artesian-water Suppy of the Dakota Sandstone in North Dakota, with Special Reference to the Edgeley Quadrangle," U. S. Geol. Surv. Water-supply Paper 520-E, p. 94, 1925.

and passes into Canada. In the vicinity of the Black Hills uplift in western South Dakota, this trough is decidedly asymmetric with steeply-dipping Cretaceous and older rocks cropping out along the western flank. Darton [17] has delineated the general features of the southern portion of this trough by contours drawn as though on the top of the Dakota. Thom and Dobbin [18] have sketched structure contours for the northern half of the trough, also on the Dakota sandstone ("First Cat Creek sand"). This horizon is 1500 feet above sea level in north-central Kansas, and slightly more than 600 feet below sea level in northwestern South Dakota. In the deepest part of the trough, the Williston basin of west-central North Dakota and northeastern Montana, the key horizon is more than 3500 feet below sea level. The magnitude of this primary structural feature may be a critical factor in the geographic distribution of saline ground waters, as is pointed out in a subsequent paragraph.

ORIGIN OF THE GROUND WATERS.

Russell [19] accounts for the presence of water in detached sandstone lentils by the assumptions that the sands were saturated with water at the time of deposition and that in addition water has been squeezed out of the overlying shales into the sandstones during the process of compaction. Modification of these assumptions, however, is necessary. Inasmuch as the compressibility of a mass of sand or of sandstone is much greater than the compressibility of water or of the individual sand grains, compaction of the sandstone lentil under the load of overlying shales would induce therein a hydrostatic pressure greater than the pressure existing in any overlying stratum. Therefore, compaction of the shales could not force water downward into the sandstone lentils, unless the connate water of those lentils was displaced along a path which

[17] Darton, N. H., "The Structure of Parts of the Central Great Plains," U. S. Geol. Surv. Bull. 691, pp. 1–26, 1919.

[18] Thom, W. T., Jr., and Dobbins, C. E., "Stratigraphy of the Cretaceous-Eocene Transition Beds in Eastern Montana and the Dakotas," *Geol. Soc. Amer. Bull.*, 35, p. 482, 1924.

[19] Russell, W. L., *op. cit.*, pp. 151–4.

was more permeable than the path vertically upward across the strata of shale. But if the sandstone lentils were detached and embedded in shale which prevented lateral movement of the water, as Russell suggests, such displacement was impossible. Hence, the corollaries of Russell's hypothesis lead to the alternative conclusions that either the sandstones of the Dakota basin contain connate water to which no accessions had been made prior to the drilling of the first artesian well, or the connate water has been in part or in whole displaced by lateral movement. But a texture of beds which would permit lateral movement of water during compaction, would also permit lateral movement across the basin from the present outcrops.

After a well was drilled to the hypothetical sandstone lentil, further compaction of the shale might squeeze water into the sandstone. If compaction is now proceeding at an appreciable rate, the walls of a well should seep salt water from the shale during the process of drilling. Although no such phenomenon is known to have been observed in the Dakota basin, it is not likely that it would be detected under the ordinary dilling procedure. Furthermore, the water discharged from wells should become progressively more salty. Such is not known to be the case, although the available data are inadequate to detect a slow increase in salinity of the water.

CHEMICAL CHARACTER OF THE GROUND WATERS.

Russell's [20] hypothesis that the differences in chemical composition of the waters of the Dakota basin are essentially due to differences in the conditions under which the water-bearing beds were deposited is considerably weakened when the chemical analyses [21] are studied in detail. All of the waters represented are much

[20] Russell, W. L., *op. cit.*, pp. 151–2.

[21] Shepard, J. H., "The Artesian Waters of South Dakota," South Dakota Agr. Coll. and Exp. Sta. Bull. 41, 1895; Bull. 49, 1896. Darton, N. H., Preliminary Report on the Geology and Underground Water Resources of the Central Great Plains, U. S. Geol. Surv. Prof. Paper 32, pp. 341, 347, 353, 355, 356, and 370, 1905; "Geology and Underground Waters of South Dakota," U. S. Geol. Surv. Water-supply Paper 227, pp. 80, 99, 101, 121, 139, and 140, 1909; "Artesian Waters in the Vicinity of the Black Hills, South Dakota," U. S. Geol. Surv.

less concentrated than sea water, although it is a corollary of the hypothesis that highly concentrated saline waters should be characteristic of the marine and brackish water beds which constitute the uppermost part of the Dakota sandstone over much of the eastern part of the basin. Furthermore, none of the waters are of that chemical composition which would be characteristic of a true connate water of a continental, brackish-water, or marine environment. Adequate interpretation of these analyses requires a consideration of many factors, such as: (1) Dilution or flushing out of an original connate water by ground water of meteoric origin, (2) solution of certain constituents from rocks with which the waters have been in contact, (3) organo-chemical processes such as the reduction of sulphates by organic matter, (4) reaction between waters having different chemical composition, (5) reaction between dissolved constituents of the waters and rock constituents, (6) earth temperature, (7) pressure, and (8) deep-seated concentration.[22] The first of these factors is denied by Russell's hypothesis. The other factors apparently are not considered at length, although they seem to checkmate his suggestion that lateral variations in chemical character of the water establishes total discontinuity of permeable beds.

Furthermore, Russell [23] holds that the existence in northwestern South Dakota of a body of hot and notably salty ground water refutes the usual concept that ground waters move eastward across the artesian basin. Again, however, this position is not incontrovertible, although the inadequacy of available data does not permit a conclusive demonstration of the true hydraulic condition. It is perhaps significant that the area of notably saline waters occu-

Water-supply Paper 428, pp. 39, 40, 57, and 62, 1918. Hall, C. W., Meinzer, O. E., and Fuller, M. L., "Geology and Underground Waters of Southern Minnesota," U. S. Geol. Surv. Water-supply Paper 256, pp. 68–73, 1911. Parker H. N., "Quality of the Water Supplies of Kansas," U. S. Geol. Surv. Water-supply Paper 273, pp. 50–201, 1911. Riffenburg, H. B., "Chemical Character of Ground Waters of the Northern Great Plains," U. S. Geol. Surv. Water-supply Paper 560-B, pp. 49–51, 1925.

[22] Mills, R. van A., and Wells, R. C., "The Evaporation and Concentration of Waters Associated with Petroleum and Natural Gas," U. S. Geo. Surv. Bul. 693, pp. 67–68, 1919.

[23] Russell, W. L., *op. cit.*, pp. 140–141.

pies the deepest part of the major syncline within the State, and that its boundary as fixed by Russell coincides almost exactly with the 200-foot structure contour drawn by Darton [24] on the top of the Dakota horizon. It is not impossible that a body of saline water of density greater than unity could remain in the deepest part of the trough in a state of hydrostatic equilibrium with fluid of less density in the flanks, even though the beds were continuously permeable. Hence, the area of notably saline waters in northwestern South Dakota may be the southern extremity of a larger body of saline connate water which has not been flushed from the beds. If such is the case, ground water moving in the Lakota-Dakota beds (including the Fall River formation of Russell) from the outcrop areas in the Black Hills and in the Front Range of Wyoming and Colorado would pass to the south of the area of saline waters and then eastward and northward along the eastern limb of the trough. Critical data to prove or to disprove the existence of such a hydrostatic condition as well as such a path of ground water movement have not been amassed and studied. The concentration and detailed chemical character of the saline water is not stated by Russell and is unknown to the writer. Whether this water could properly be termed connate is wholly speculative. To make further analysis of this phase of the Dakota problem would be idle in view of the paucity of data, although the conclusion is justified that the concept of a regional movement of ground water in the Dakota basin is not refuted by the lateral variations in chemical character of the waters.

PIEZOMETRIC SURFACE AND HYDRAULIC CIRCULATION.

In discussing the variations in artesian pressure in the Dakota basin, Russell [25] sets up two fundamental relations: first, the lines of equal head or pressure as mapped by Darton [26] do not curve

[24] Darton, N. H., *op. cit.*

[25] Russell, W. L., *op. cit.*, pp. 141–4.

[26] Darton, N. H., Preliminary Report on the Geology and Underground Water Resources of the Central Great Plains, U. S. Geol. Surv. Prof. Paper, 32, pl. LIX., p. 192, 1905. Darton, N. H., "Geology and Underground Waters of South Dakota," U. S. Geol. Surv. Water-supply Paper 227, pl. XI., 1909.

around those areas in which the Dakota sandstone crops out in the Black Hills and in the eastern part of South Dakota; second, the head is lower in the major valleys than on the adjacent uplands, particularly in the valleys of the Missouri and James rivers in the southeastern part of the State. From these it is inferred that the theory of artesian circulation is false. The validity of Russell's fundamental relations is tested below.

First, Darton's maps depict the piezometric surface for the Lakota-Dakota beds—an imaginary surface marking the elevations to which water would rise from the beds under hydrostatic pressure—by lines of equal static level, the cartographic units employed being horizontal scales of approximately 20 and 40 miles per inch and a contour interval on the piezometric surface of 100 feet. The disproportion between these units and the gentle slope of the piezometric surface, or hydraulic gradient—1½ to 15 feet per mile for the greater part of the basin—demands wide limits of tolerance in any interpretation of the data presented. Nevertheless, it can be stated without reservation that the lines of equal head most emphatically to curve around the areas of outcrop, both in the Black Hills and in eastern South Dakota. Furthermore, in those same areas the lines of equal head are essentially parallel to the structure contours drawn on the top of the Dakota sandstone. Russell's [27] denial of these relations is quite unwarranted.

Finally, adequate interpretation of variations in artesian head within any small part of the basin—such as is involved in Russell's suggested relation between artesian head and surface topography—may be difficult or impossible, on account of mechanical limitations. Field observations of head must be made with great care and must be rigidly controlled by instrumental levelling if they are to be reliable. The loss of head in a given well due to a leaky casing or the loss of head about an area of natural ground water discharge may be equivalent to the normal slope of the piezometric surface in a distance of several miles. A given series of observations on a group of wells is of little weight unless made

[27] Russell, W. L., *op. cit.*, pp. 141–2, 154.

at essentially the same time. Meinzer [28] points out that several hours may elapse after a well has been closed before the normal pressure can be determined by a gage. Upon these mechanical limitations are superposed uncertainties due to unequal rates of draft in different parts of the basin. Furthermore, it was very generally assumed prior to 1900 that the head in the Dakota basin was constant, and measurements of pressure made at widely different times were regarded as of equal weight. Meinzer [29] believes however, that the decline in head was probably comparatively rapid during the first years of the basin's development. The rapidity with which artesian pressures may be dissipated by the discharge of a relatively small volume of water when a basin is first developed is shown by a deep test well drilled recently in the northern Punjab region of India. A certain aquifer of this well developed an artesian pressure of 500 pounds per square inch when it was first penetrated, although the pressure diminished about 40 per cent.[30] in two months time. This diminution is equivalent to a subsidence of the static level amounting to 460 feet. The possibility of a similarly rapid decline in artesian head—undetected and unmeasured—must be read into all data of the Dakota basin. Full consideration of these factors probably holds in large part the explanation of the apparent decrease of head in the valleys of the Missouri and James rives in Potter County and elsewhere. Russell's supposition that "a number of the measurements (of pressure) were taken before the production of wells was large enough to effect a marked lowering of the head" is not well founded. Moreover, his analysis of the directions of ground water movement within a portion of the area of artesian flow—Potter County—is inadequate in that it suggests the unsound assumption that the direction of movement is the same as in that large part of the structural basin within which flowing wells can not be obtained.

As an alternative to the theory of regional movement of ground

[28] Meinzer, O. E., oral communication.

[29] *Op. cit.*

[30] Anderson, R. Van V., "Tertiary Stratigraphy and Orogeny of the Northern Punjabe," *Bull. Geol. Soc. Amer.*, vol. 38, pp. 665–720, Dec. 30, 1927.

water within the basin, Russell [31] concludes that the waters of the Dakota-Lakota beds (also Fall River of Russell) occur in a series of disconnected lentils, that the artesian pressure is due wholly to the weight of the overlying rocks, and that there is no regional movement of water. Several corollaries of this hypothesis serve as tests of its validity.

First, each separate body of ground water should be isopiestic, that is, its piezometric surface should be a horizontal plane; further, two or more such isopiestic bodies could be under the same head only when the unit loads due to overlying strata were equal. Hence, if the lentils are of limited extent and lie in a horizontal plane the apparent regional piezometric surface would conform closely to the surface topography. If, on the other hand, the horizontal dimensions of the lentils approach those of the major topographic features, conformity would not exist. These relations can not be adequately tested by the available data, although it is not impossible that they could be tested in a rigorous manner in the field, provided the effect of unequal rates of local draft could be evaluated.

Second, the original artesian pressure measured at the ground surface should be a direct function of the thickness of the rocks which overlie the water-bearing sandstone. Consequently the greatest original pressures should have been found at well sites on the topographic summits along the deepest part of the major syncline, which lies in western South Dakota. Such is not the case; the greatest pressures are found on the eastern flank of the trough where the overburden upon the sandstone is only moderately thick and the pressures decrease westward toward the axis of the trough as the thickness of the overburden increases.

Third, the first well drilled into one of the detached lentils should have a pressure comparable to that of the original well drilled into any other lentil even though many years earlier. This relation does not seem to be the true one.

Fourth, the lowering of the head by exceptionally heavy draft at one locality—as by those cities whose municipal supply is drawn

[31] Russell, W. L., *op. cit.*, pp. 152–156.

from the Dakota sandstone—should not be felt beyond the limits of the lentil tapped. Russell estimates the area within which the head has been lowered by the municipal wells at Aberdeen as 1,600 square miles, although his most extensive lentil is but 5 or 10 miles in maximum dimension.[32] Clearly this reduces to an insolvable dilemma if Russell's hypothesis is accepted.

It appears, therefore, that Russell's hypothesis of the ground waters occurring in wholly detached lentils and of the artesian pressure being due wholly to the weight of the overlying rocks, entails difficulties which throw grave doubt over its validity.

The theory that artesian aquifers are compressed when the artesian pressure is decreased and are expanded when the pressure is increased, has been suggested recently by Meinzer [33] as one of the fundamental principles of the artesian condition. Russell's [34] hypothesis accepts this principle in a restricted sense, in that it assumes compaction or compression of the water-bearing sandstone under the load of overlying strata as the artesian head decreases concurrently with continued draft. His hypothesis proposes, however, that elastic compaction of the water-bearing sandstone is the sole mechanism maintaining artesian pressure in the Dakota basin, whereas Meinzer's theory also conceives elasticity as a secondary factor which modifies an artesian condition established by hydraulic pressure. Hence, a test of Russell's hypothesis would be in no sense a test of the principle of elasticity of artesian aquifers in the broad sense.

SUMMARY AND CONCLUSION.

It would seem that the evidence of the stratigraphy, the variations in quality of the water, and the variations in the artesian pressure is not conclusive in disproving the conventional concept of regional movement of ground water in the Dakota artesian basin when the validity of that evidence is tested on a regional

[32] Russell, W. L., *op. cit.*, pp. 148–9 and 144.

[33] Meinzer, O. E., and Hard, H. A., *op. cit.*, pp. 90–93. Meinzer, O. E., "Compressibility and Elasticity of Artesian Aquifers," ECON. GEOL., vol. 23, No. 3, pp. 263–291, 1928.

[34] Russell, W. L., *op. cit.*, pp. 146–151.

scale. If ground waters obey the usual laws of hydraulics, they should move from areas of high pressure head to areas of low pressure head. From this has followed the usual concept of an eastward movement of the waters of the Dakota basin. Experiment has shown that such movement of ground water can occur in permeable materials similar to those of the Lakota-Dakota beds under a hydraulic gradient as low as any existing in the Dakota basin, and that the rate of migration remains approximately proportional to the hydraulic gradient [35] as postulated in Darcy's law. This concept of regional movement does not infer that for every point within the basin the direction of ground water movement is due eastward, but only that the movement is generally toward the eastern side of the basin. Furthermore it does not infer that the rate of movement is high.[36]

The hydrology of the artesian condition has hitherto been investigated largely in a qualitative way and our knowledge of this field has suffered from a lack of specific data. However, effective methods of quantitative investigation which are now being evolved have disclosed such fundamental principles as that of elasticity of artesian aquifers, and, it is hoped, will ultimately yield a comprehensive and quantitatively sound analysis of the artesian problem.

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WASHINGTON, D. C.

EFFECT OF EARTHQUAKES ON ARTESIAN WATERS.

Sir: The paper by W. L. Russell on "The Origin of Artesian Pressure" and O. E. Meinzer's paper on "Compressibility and Elasticity of Artesian Aquifers" are of much interest, for they emphasize a factor in artesian water supply that has been very largely neglected. There is one source of evidence bearing on the problem to which attention has not been called, and that is the effect of severe earthquakes on artesian waters.

[35] Stearns, N. D., "Laboratory Tests on Physical Properties of Water-bearing Materials," U. S. Geol. Surv. Water-supply Paper 596-F, pp. 144–169, 1927.

[36] Meinzer, O. E., and Hard, H. A., *op. cit.*, p. 94.

An increase in the discharge of water from springs following earthquakes is common, and often the flow of water in streams is noticeably greater. Similar effects have been observed in artesian wells, but in all of these cases the flow gradually returns to normal.

The California earthquake of 1906 produced marked effects on the artesian belt near the head of San Francisco Bay.[1] Wells that were not flowing prior to the shock began to flow, and flowing wells had their pressure greatly increased. A well near Alviso, at the head of the bay, furnishes a good illustration. For several years prior to the earthquake it had been necessary to pump water from the well and a wind-mill had been installed for that purpose. At the time of the earthquake the well-casing was driven two feet out of the ground, wrecking the pump, and the well began to flow under heavy pressure. In the course of a few weeks, however, the pressure decreased until it reached a point where pumping was again necessary.

STEPHEN TABER.

UNIVERSITY OF SOUTH CAROLINA,
COLUMBIA, S. C.

[1] Taber, Stephen, "Some Local Effects of the San Francisco Earthquake," *Journal of Geology*, vol. 14, p. 315, 1906.

REVIEWS

The Elements of Economic Geology. By J. W. GREGORY. Pages 312. Figs. 63, cloth. E. P. Dutton & Co., New York. Price $3.25.

Many of the views held by the author of this little textbook will not find favor among most teachers of economic geology. The statements concerning some ores will seem so explicit that the uninformed reader will be led to believe that the question as to their origin has been answered, whereas it may still be under active discussion. The teacher will have to modify so many of the conclusions expressed by its author that he will doubt the advisability of placing the book in the hands of the young student.

A part of the objection to the use of the book as a text arises from the fact that the author believes "more ores as due to the deposition, solution and redeposition of sedimentary grains" than do most geologists, and accepts "fewer ores as due to direct igneous processes." He regards "the source of most metals as an ore-zone beneath the ordinary igneous rocks of the crust and not the igneous rocks themselves." His thesis, stated without discussion, is that the greater part of the earth is the barysphere composed mainly of a nickel-iron alloy, that the core, or centrosphere, is fluid and that the lithosphere, about 40 miles thick, may be regarded as a slag which floated upward while the heavier constituents sank and formed the barysphere. "The barysphere," he writes "doubtless passes into the lithosphere through an ore-zone, rich in silicates and metallic sulphides." Many ores come from this. He presents a brief argument in opposition to the belief that metallic ores are connected with igneous rocks, concluding it with the statement that "as ores of different kinds exist in one igneous rock and ores of the same kind in different igneous rocks, the source of most ores is outside the rock in which they occur." The opinions of American and European geologists seem to have little weight in the discussion, as nearly all references are to the publications of British and South African workers.

The terminology employed in the book is not in accord with that of most writers. A mineral is anything that is mined. Coal, petroleum, slate are minerals. A lode is any mineral deposit. The terms lode and vein are used interchangeably, in some places to the confusion of the reader. The authorities quoted to support his usage are almost exclusively British writers, among whom are Chaucer and Shakespeare.

The book is valuable for its numerous references and its many descriptions of little-known deposits, especially of those described by the

geologists of the British Empire. The author has evidently not read the reports of American authors with the care that he has given to those of his own countrymen. For instance he states that in the Lake Superior district the "iron formation belongs to the Keewatin series, of which the typical rock is a basic pillow-lava."

In spite of its weaknesses the book is a good one to have upon one's book shelves because of its wealth of references to the writings of men who have worked in the far corners of the earth. It does not appeal to the reviewer as a satisfactory textbook, however, because of its neglect of the views of American geologists and its meager descriptions of some of the most important ore-producing districts in the United States, such as the copper and iron-ore districts bordering Lake Superior. The great iron-ore deposits are dismissed in about one page on which are two sketches—one after H. Garde and the other after Van Barneveld. The origin of the native copper deposits is settled in seven lines as follows: "The rocks near the ore have been traversed by hot alkaline plutonic water, which probably obtained the copper by the solution of detrital grains in the sandstones. The channels form the shoots, some of which enter the lavas; the reduction of the solution by oxidation of ferrous iron in the diabase or of some ferrous mineral in the conglomerate led to the deposition of the native copper."

An interesting feature of the book, which is not usually found in treatises on economic geology, is a discussion of water supply, coastal works and the principles of anti-earthquake construction.

W. S. Bayley.

The Use of the Torsion Balance in the Investigation of the Geological Structure of Southwest Persia. By W. F. P. McLintock and J. Phemister. Summary of the Progress of the Geol. Survey of Great Britain for 1926, Appendix II., pp. 168 to 196. London, 1927.

This is the report of two officers of the survey who through the invitation of the Anglo Persian Oil Company were sent to Persia to investigate the geophysical work of the company. The paper gives the results of three torsion balance traverses, the interpretation of the results and the success of the torsion balance in indicating the partially known geology, discusses briefly the theory of the torsion balance and the interpretation of torsion balance surveys, and gives examples of the anomalies produced by different types of geologic structures. A selected bibliography of papers on the torsion balance is appended. It is an excellent and interesting paper.

A not uncommon but serious mistake has been made in the preliminary statement of why the torsion balance works. The torsion system of the balance rotates not because there is any appreciable difference in the

value and direction of gravity at the two weights, but because the warping of the equipotential (level) surfaces and of the lines of the vertical produces a small horizontal component of gravity at the two weights. Within the sensitivity of the torsion balance, this component of gravity is identical in magnitude and exactly opposite in absolute direction but the same in rotational effect at the two weights.

A Gravity Survey over the Swynnerton Dyke, Yarnfield, Staffordshire. By W. F. McLintock and J. Phemister. *The Mining Magazine*, December, 1927.

A line of torsion balance stations was run across the supposed prolongation of a basalt dike, where the dike was supposed to be covered with glacial drift. The results show the presence of the dike with the clearness of a textbook example.

Donald C. Barton.

Tabellen zur allgemeinen und speziellen Mineralogie. By Paul Niggli. Pp. 300, numerous figures. Gebrüder Borntraeger, Berlin 1927. Price 9.30 M.

In this volume Professor Niggli adds to the tables that aid in the determination of minerals. The first part of the book consists of a summary of the forms and symmetry in the various crystal systems. The second part of 150 pages consists of determinative tables for the more common minerals, using a primary basis of crystal form. Numerous figures of crystals make this essentially a condensed crystal atlas, and to the reviewer suggest a valuable use in the determination of heavy minerals, especially those of volcanic rocks, under the microscope. Other tables of color, hardness, streak, specific gravity, occurrence of minerals, useful ores and precious stones, make up 65 pages. The last part of the book is taken up with tables for the optical determination of minerals. The basis of classification is optic character, sign, colored or colorless in thin section, and birefringence. This book collects considerable information in a convenient and usable form, and covers all the mineral properties commonly used in determination except blowpipe and chemical tests. The printing and figures are clear, and the book is substantially and pleasingly bound.

Freleigh F. Osborne.

Eine Studie über den Braun-Jurass im nordöstlichen Schwaben und seine Eisenöolithflöze. By Dr. Friedrich Schleh. Pp. 39, index. *Abhandl. zur prakt. Geol. und Bergw.*, Georg Berg. Berlin, Geologische Landesanstalt.

The above paper on the oölitic iron deposits of northeastern Swabia, Bavaria, deals with an area about 80 miles long in a northeast-southwest

direction. Ore occurs at five horizons in flat-lying limestone and clays with some intercalated sandstones.

Most of the beds contain abundant marine fossils of the Brown Jura (middle Jurassic) period. The ore strata average 20 per cent. of iron and contain some galena, sphalerite and pyrite. Gangue minerals are dolomite, calcite, sericite and silica. The iron is in the form of a hydrous oxide and contains some phosphorus and manganese. The estimated ore reserves are thirty-two million tons.

The presence in the ore of fossil shells that have not been affected by meteoric waters is regarded as indicative of a syngenetic origin. The lack of mineralization in the intercalated sandstone points to the same conclusion. The abundance of fossils is regarded as indicative of sedimentation in fairly deep water.

Much of the paper is devoted to detailed accounts of local variations, to a faunal list and to lithological descriptions.

F. A. NICKELL.

Grundwasserkunde. By W. KOEHNE. Pp. 291, figs. 100. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 1928. Price, 18 Marks.

A knowledge of the character and the distribution of the groundwater and of the nature of groundwater reservoirs is of so much importance to construction, mining and sanitary engineers, and to geologists, that a systematic discussion of the subject is becoming very desirable.

In Dr. Koehne's book the entire subject of groundwater is treated under twelve heads, the most important of which are as follows: (1) Definitions; (2) The passage of water into the ground; (3) The saturated zone; (4) The relation between groundwater reservoirs and geology; (5) Important hydraulic formulas; (6) The effects of canals, mines, etc. upon the flow of the groundwater; (7) Measuring and estimating the quantity of groundwater; (8) The systematic observation of groundwater movements; and (9) Relation between groundwater and husbandry. One appendix of 10 pages lists important publications on the groundwater, and another of 8 pages is a lexicon of German terms. The book is not technical, but is rather a general and elementary treatise on groundwater, its origin, its distribution and its use.

W. S. BAYLEY.

BOOKS RECEIVED

Oil and Gas Development and Possibilities in East-Central Illinois. By L. A. MYLIUS. 205 pp., 13 figs.; 31 maps, tables of well data. Illinois State Geol. Surv. Bull. 54, 1928 (July). Price, $1.50.

Summarized geology; pools; well-logs; operations; recommendations.

Mineral Resources of the United States, 1925: Part I., Metals; Part II., Non-Metals. U. S. Bureau of Mines, Washington, 1928 (July).

Water Resources of Virginia. By J. J. DIRZULAITIS and G. C. STEVENS. 510 pp., 8 pls. Virginia Geol. Surv. Bull. 31, Richmond, 1927 (June, 1928).

Stream flow records of Virginia streams and summary of water power development on the Potomac River system.

Bituminous Coal Fields of Pennsylvania, Coal Resources. By J. F. REESE and J. D. SISLER. 153 pp. Penn. Geol. Surv. Bull. M–6, Pt. III., 1928 (July).

Original computations of coal reserves of each county.

Die Pflanzenreste des Mitteldeutschen Kupferschifers und ihre Einschaltung in Sediment. By JOH. WEIGELT. Pp. 592, figs. 14, pl. 35. Fort. d. Geol. u. Pal. Band VI., Heft 19. Borntraeger, Berlin, 1928 (July). Price, 20 M.

Careful study of kupferschiefer plants; well illustrated.

Investigations in Ceramics and Road Materials, 1926. 66 pp. Canada Dept. of Mines, Mines Branch, No. 690. Ottawa, 1928 (July).

Brick manufacture and sizes; moulding sand, kaolin, crushed stone.

Production and Development Problems in the Powell Oil Fields, Navarro, Texas. By H. B. HILL and C. E. SUTTON. 123 pp., 34 figs. U. S. Bur. of Mines, Bull. 284, 1928 (August). Price, 45 cents.

Geology; operating methods; water problems; production statistics; of the enormously productive Powell field.

Recent Oil and Gas Prospecting in Mississippi, with a Brief Study of Subsurface Geology. By RALPH E. GRIM. 98 pp., 6 figs. Miss. Geol. Surv. Bull. 21, 1928 (August).

Recent gas wells point to oil possibilities; this subject is carefully considered.

Economic Geology of the Castlegate, Wellington, and Sunnyside Quadrangles, Carbon County, Utah. By FRANK R. CLARK. 165 pp., 21 pl., map, index. U. S. Geol. Surv. Bull. 793, 1928 (June).

Careful study of geology and character of the coals.

Geological Survey of Great Britain, Summary of Progress, 1927, Part I. London, 1928 (Sept.). Price, 45 cents, at the British Library of Information, 5 E. 45th St., New York.

SOCIETY OF ECONOMIC GEOLOGISTS

At the last meeting of the Council of the Society of Economic Geologists, President Emmons was requested to appoint a Committee on Policy. He has appointed the following: R. A. F. Penrose, Jr. (Chairman), J. Volney Lewis, and George H. Garrey. This committee will make a careful study of the affairs of the Society and recommend such changes in organization and administration as it considers desirable. Suggestions from members as to these subjects should be sent to the Chairman, R. A. F. Penrose, Jr., Bullitt Building, Philadelphia.

H. Foster Bain has been appointed representative of the Geological Society of America to the Council of the Society of Economic Geologists.

H. G. Ferguson has been appointed representative from the Society on the Division of Geology and Geography of the National Research Council for a term ending 1931. He succeeds M. R. Campbell. F. L. Hess is the other representative of the Society.

President Emmons has appointed the following committee to nominate officers for the year 1929: Alan M. Bateman (Chairman), E. F. Burchard, G. F. Loughlin.

The Society will hold its Annual Meeting with the Geological Society of America in New York on December 27, 28, and 29.

SCIENTIFIC NOTES AND NEWS

J. M. Hill has resigned his San Francisco office with the U. S. Division of Mineral Resources to take up private practice. He will continue to publish "Interpretative Facts."

F. L. Ransome, of Pasadena, Calif., has lately made examinations for the City of Los Angeles of the Hollywood and other dams, and for Pasadena of a site in San Gabriel Canyon, also for the Southern California Edison Company of a site on the upper San Joaquin River. He completed in July an examination of the Simon silver-lead mine near Mina, Nevada, and went to Mexico to investigate for the Mexican Government reservoir and dam sites in Sonora and Chihuahua.

R. van A. Mills has resigned from the U. S. Bureau of Mines, and is now petroleum engineering editor of the *Oil and Gas Journal*, Tulsa, Okla.

Walter W. Bradley succeeds Lloyd L. Root as state mineralogist of California. Mr. Root has resigned to take up private practice as a consulting engineer.

H. B. Lumsden, of the Canadian Pacific Railway, has been in British Columbia making arrangements for a survey of the non-metallic mineral resources of western Canada.

H. W. Hoots, who has been in charge of geological work for the U. S. Geological Survey in California, is now on the geological staff of the Union Oil Company.

R. E. Somers has resigned as head of the Department of Geology at the University of Pittsburgh to join the geological staff of the Gulf Oil Corp., Pittsburgh.

R. C. Wallace, formerely head of the Department of Geology at the University of Manitoba, is now President of the University of Alberta.

Frederick G. Clapp has resumed consulting practice at 50 Church Street, New York, having completed his engagement as petroleum engineer to the Imperial Government of Persia.

C. P. Berkey and W. J. Mead are members of the committee appointed by President Coolidge to report on the Boulder Dam site.

Millard K. Shaler, of Brussels, Belgium, has been awarded the honorary degree of Doctor of Engineering by Louvain University.

E. K. Soper, of Los Angeles, is now consulting geologist for the Texas Company of California.

G. H. Blanchette is exploring the territory around Hudson Bay, in search of minerals.

D. C. Barton will return from Europe late in September.

The Petroleum Division of the American Institute of Mining and Metallurgical Engineers will meet at Tulsa, Okla., October 18 and 19, before the International Petroleum Exposition on October 20.